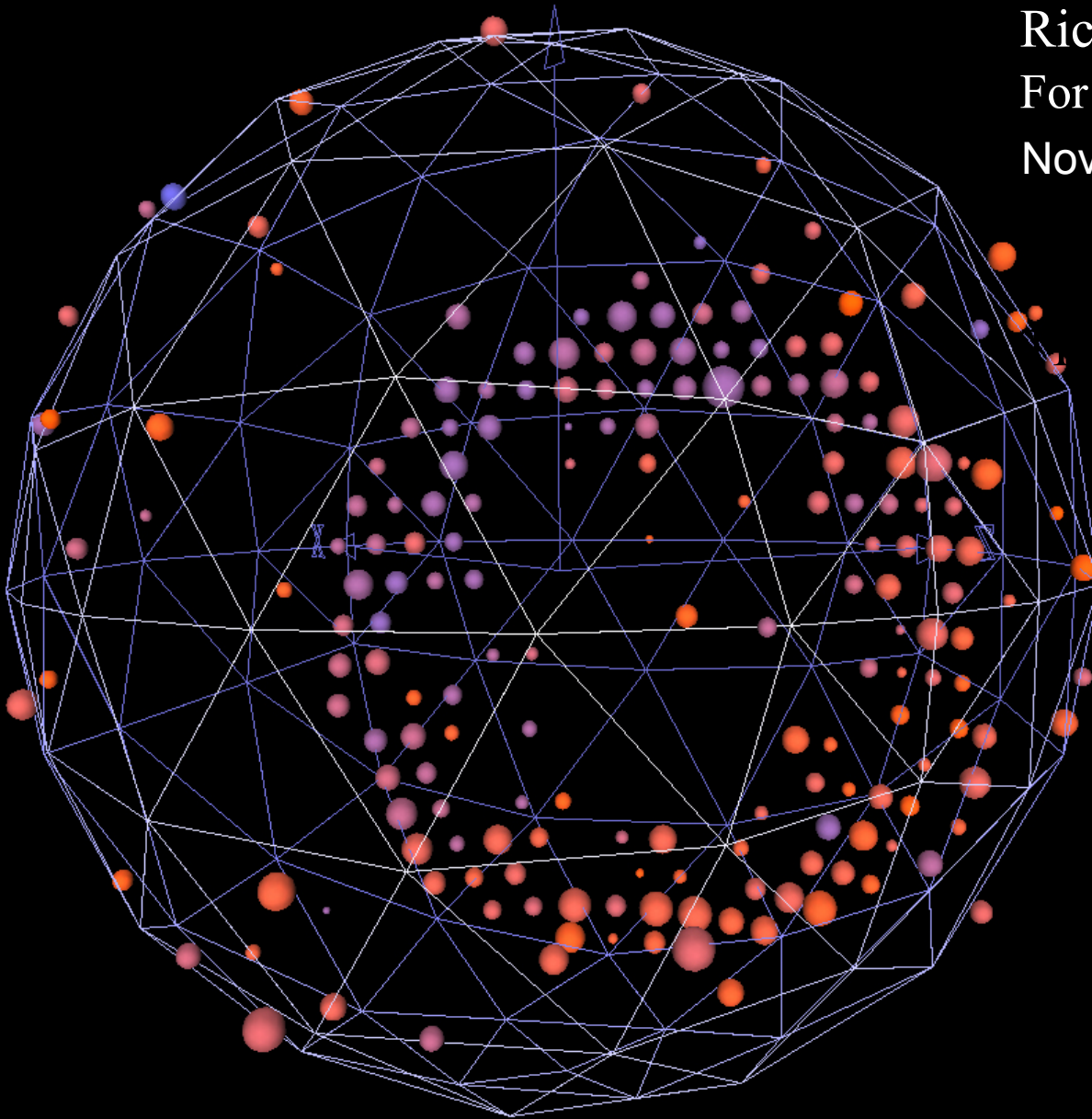


MiniBooNE Request for Extended Running

Richard Van de Water
For the MiniBooNE collaboration
Nov 5, 2010 PAC



Outline:

- The Request for extended running
- Motivation for MiniBooNE; Testing the LSND anomaly.
- MiniBooNE design strategy and assumptions
- Previous neutrino oscillation results
- Antineutrino oscillation results for $5.66\text{E}20$ POT
- Physics motivation for more running
- Logistics of further running
- Future analysis
- Summary
- Preliminary look at recently collected $1.16\text{E}20$ POT

A Request for Further MiniBooNE Antineutrino Running

October 5, 2010

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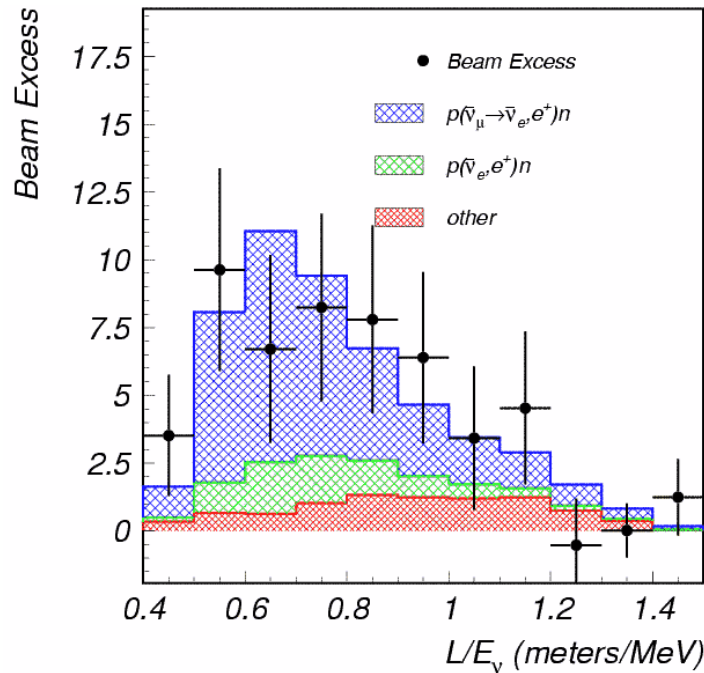
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The Request

- ▶ MiniBooNE requests additional antineutrino running to collect a total of 15.0×10^{20} POT in antineutrino mode. This will allow a powerful statistical check of the current MiniBooNE antineutrino oscillation result that is consistent with LSND. The experiment further requests that these POT be delivered by early 2013 if possible.

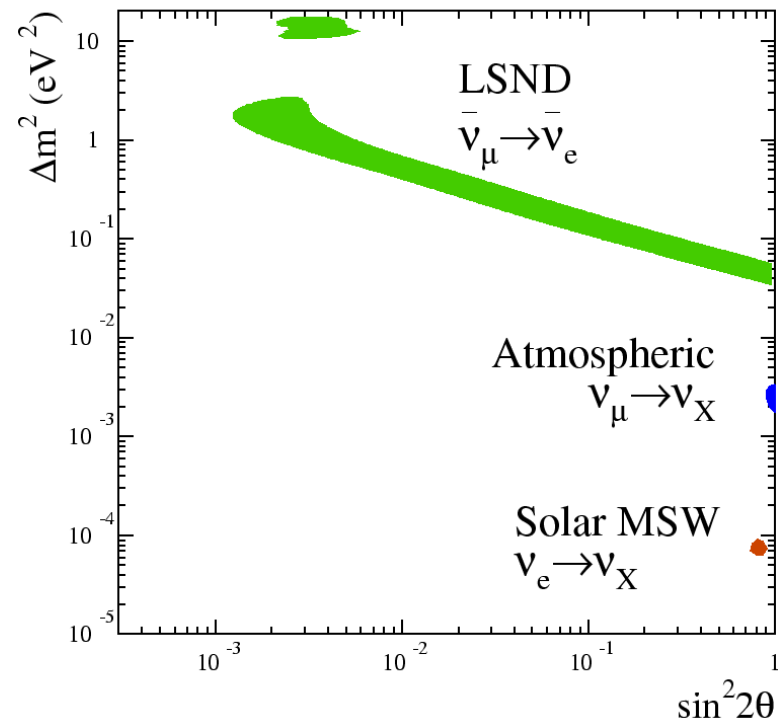
Motivation for MiniBooNE: The LSND Evidence for Oscillations



LSND Saw an excess of $\bar{\nu}_e$:
 $87.9 \pm 22.4 \pm 6.0$ events.

With an oscillation probability of
 $(0.264 \pm 0.067 \pm 0.045)\%$.

3.8 σ evidence for oscillation.



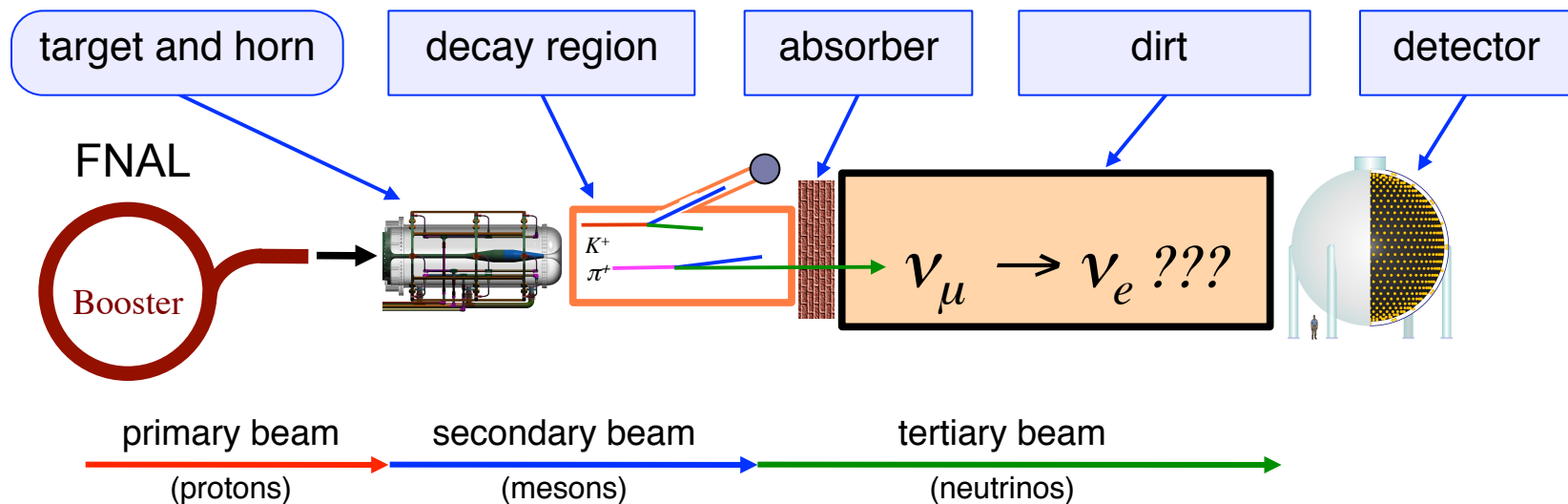
The three oscillation signals cannot be reconciled without introducing Beyond Standard Model Physics!

MiniBooNE was designed to test the LSND signal

Keep L/E same as LSND
while changing systematics, energy & event signature

$$P(\nu_\mu \rightarrow \nu_e) = \sin^2 2\theta \sin^2(1.27 \Delta m^2 L/E) \rightarrow \text{Two neutrino fits}$$

LSND:	$E \sim 30 \text{ MeV}$	$L \sim 30 \text{ m}$	$L/E \sim 1$
MiniBooNE:	$E \sim 500 \text{ MeV}$	$L \sim 500 \text{ m}$	$L/E \sim 1$

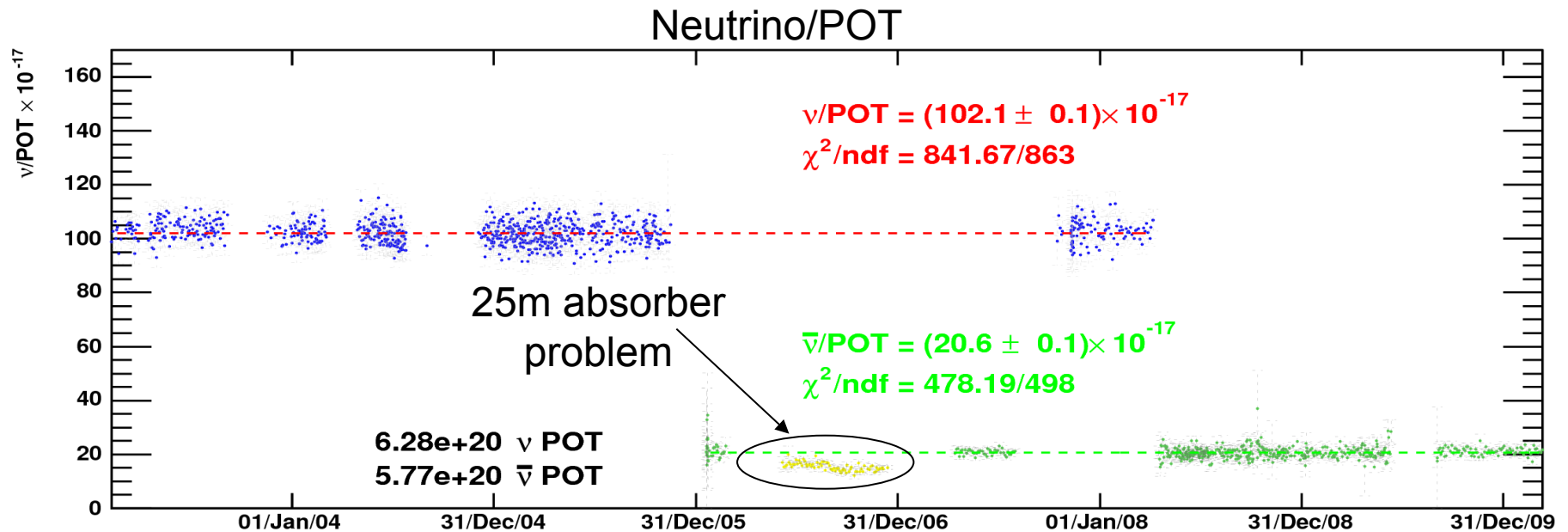
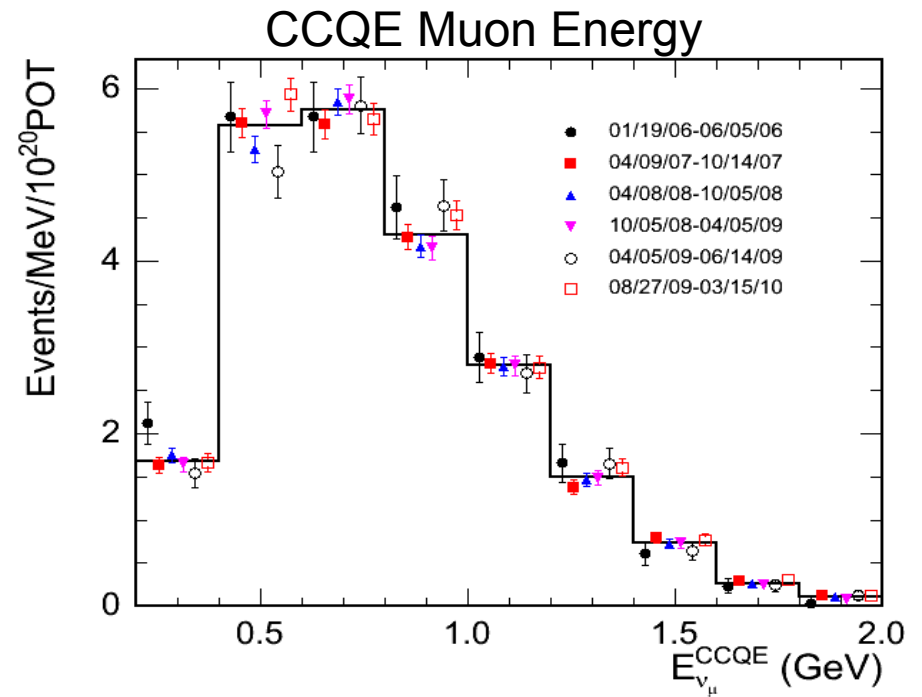


Neutrino mode: search for $\nu_\mu \rightarrow \nu_e$ appearance with $6.5E20$ POT \rightarrow assumes CP/CPT conservation
Antineutrino mode: search for $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ appearance with $5.66E20$ POT \rightarrow direct test of LSND

FNAL has done a great job delivering beam!

Data Stability

- Beamline and Detector stable throughout the run



$\bar{\nu}_e$ Event Rate Predictions

$$\text{\#Events} = \text{Flux} \times \text{Cross-sections} \times \text{Detector response}$$

**External measurements
(HARP and E916)**
 ν_μ rate constrained by
neutrino data

**External and MiniBooNE
Measurements**
 $\pi^0, \Delta \rightarrow N\gamma$, dirt, and intrinsic
 $\bar{\nu}_e$ constrained from $\bar{\nu}_\mu$ data.

**Detailed detector
simulation and PID**
**Checked with neutrino
data and calibration
sources.**

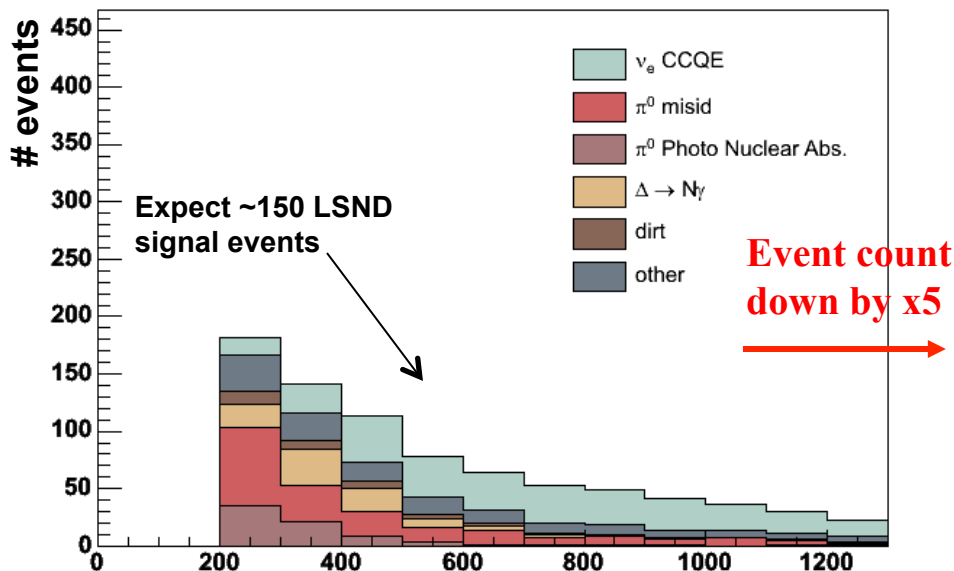
- A. A. Aguilar-Arevalo et al., “Neutrino flux prediction at MiniBooNE”, Phys. Rev. D79, 072002 (2009).
- A. A. Aguilar-Arevalo et al., “Measurement of Muon Neutrino Quasi-Elastic Scattering on Carbon”, Phys. Rev. Lett. 100, 032301 (2008).
- A. Aguilar-Arevalo et al., “First Observation of Coherent π^0 Production in Neutrino Nucleus Interactions with Neutrino Energy < 2 GeV”, Phys. Lett. 664B, 41 (2008).
- A. A. Aguilar-Arevalo et al., “Measurement of the Ratio of the ν_μ Charged-Current Single-Pion Production to Quasielastic Scattering with a 0.8 GeV Neutrino Beam on Mineral Oil”, Phys. Rev. Lett. 103, 081801 (2009).
- A. A. Aguilar-Arevalo et al., “Measurement of ν_μ and $\bar{\nu}_\mu$ induced neutral current single π^0 production cross sections on mineral oil at $E_\nu \sim 1$ GeV”, Phys. Rev. D81, 013005 (2010).
- A. A. Aguilar-Arevalo et al., “Measurement of the ν_μ charged current π^+ to quasi-elastic cross section ratio on mineral oil in a 0.8 GeV neutrino beam”. Phys. Rev. Lett. 103:081801 (2010).
- A. A. Aguilar-Arevalo et al., “First Measurement of the Muon Neutrino Charged Current Quasielastic Double Differential Cross Section”, Phys. Rev. D81, 092005 (2010), arXiv: 1002.2680 [hep-ex].
- A. A. Aguilar-Arevalo et al., “The MiniBooNE Detector”, Nucl. Instr. Meth. A599, 28 (2009).
- P. Adamson et al., “Measurement of ν_μ and $\bar{\nu}_e$ Events in an Off-Axis Horn-Focused Neutrino Beam”, Phys. Rev. Lett. 102, 211801 (2009).
- R.B. Patterson et al., “The Extended-Track Event Reconstruction for MiniBooNE”, Nucl. Instrum. Meth. A608, 206 (2009).

$\bar{\nu}_e$ Event Rate Predictions for Appearance Analysis

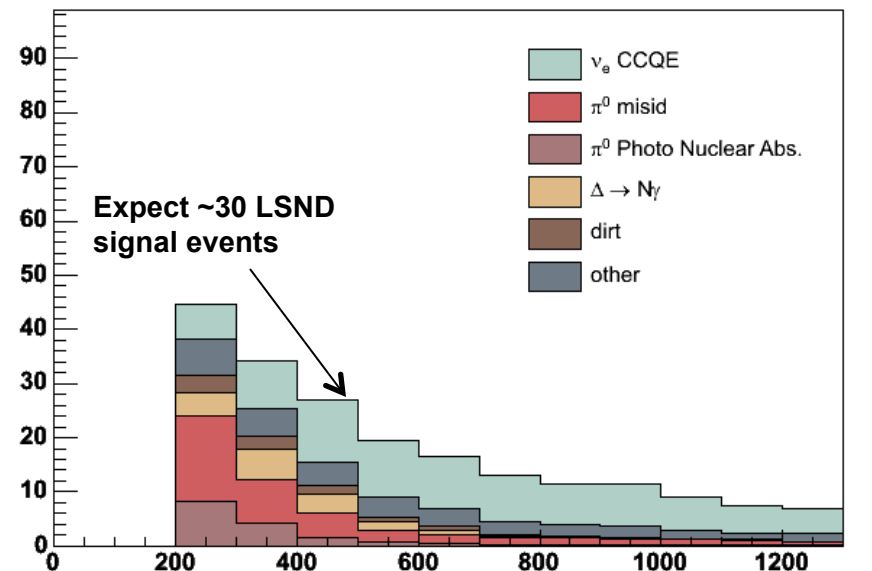
- Antineutrino rate down by a factor of 5 (reduced flux and cross section)
- Background types and relative rates are similar for neutrino and antineutrino mode.
 - except inclusion of 15.9% wrong-sign neutrino flux component in antineutrino mode
- Fit analysis and errors are similar.

$\bar{\nu}_e$ Backgrounds after PID cuts (Monte Carlo)

Neutrino 6.5×10^{20} POT



AntiNeutrino 5.66×10^{20} POT



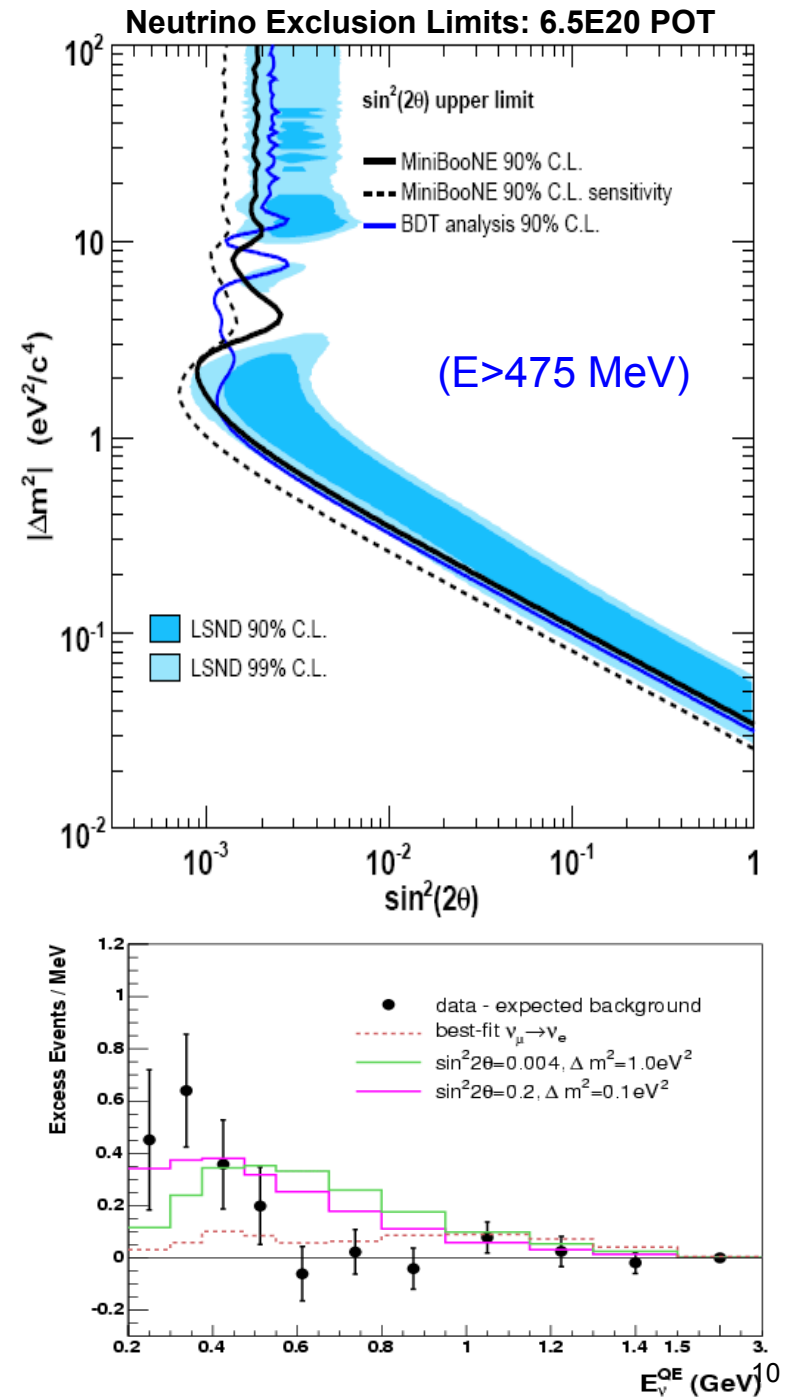
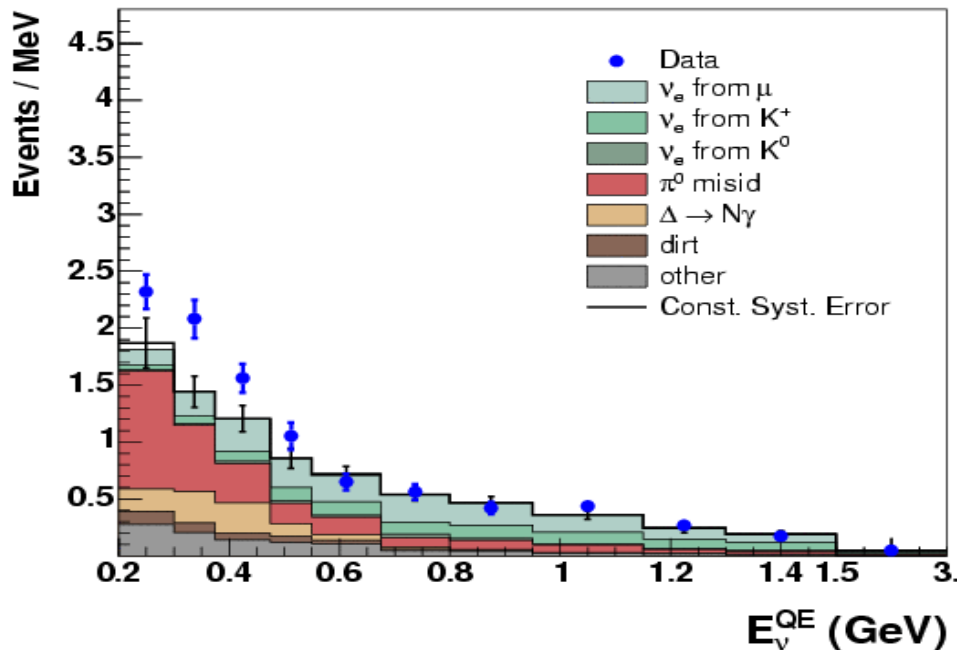
E_{ν}^{QE} = Reconstructed QE neutrino energy

(MeV)

Neutrino mode MB results (2009)

- **6.5E20 POT** collected in neutrino mode
- $E > 475$ MeV data in good agreement with background prediction
 - ➔ energy region has reduced backgrounds and maintains high sensitivity to LSND oscillations.
 - ➔ A two neutrino fit inconsistent with LSND at the 90% CL assuming CP conservation.
- $E < 475$ MeV, statistically large (6σ) excess
 - ➔ Reduced to 3σ after systematics, shape inconsistent with two neutrino oscillation interpretation of LSND. Excess of 129 ± 43 (stat+sys) events is consistent with magnitude of LSND oscillations.

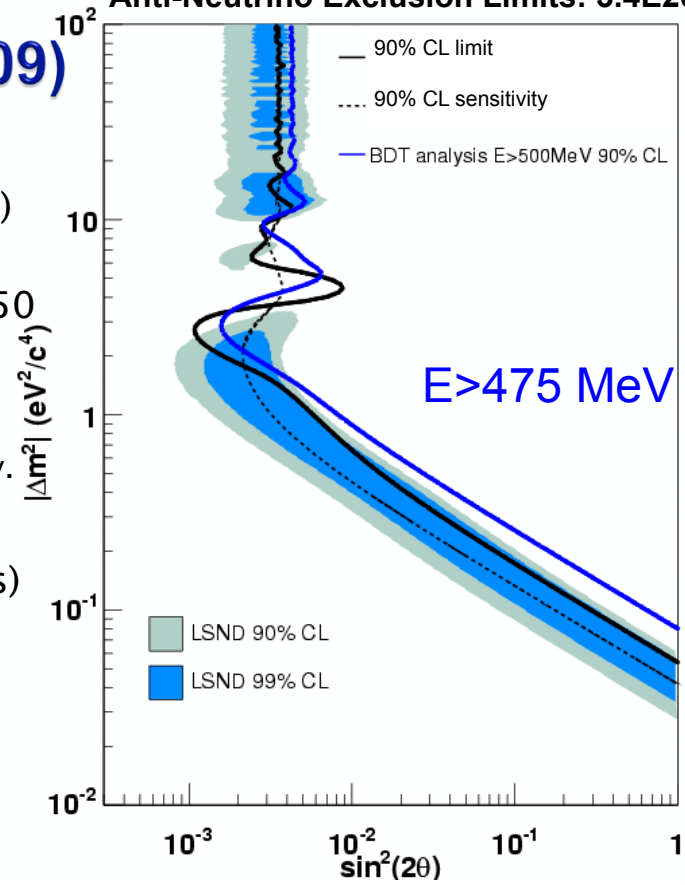
Published PRL 102,101802 (2009)



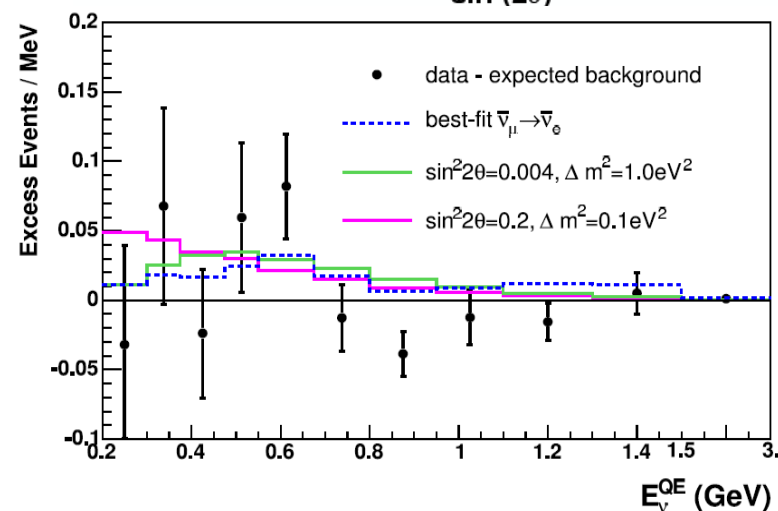
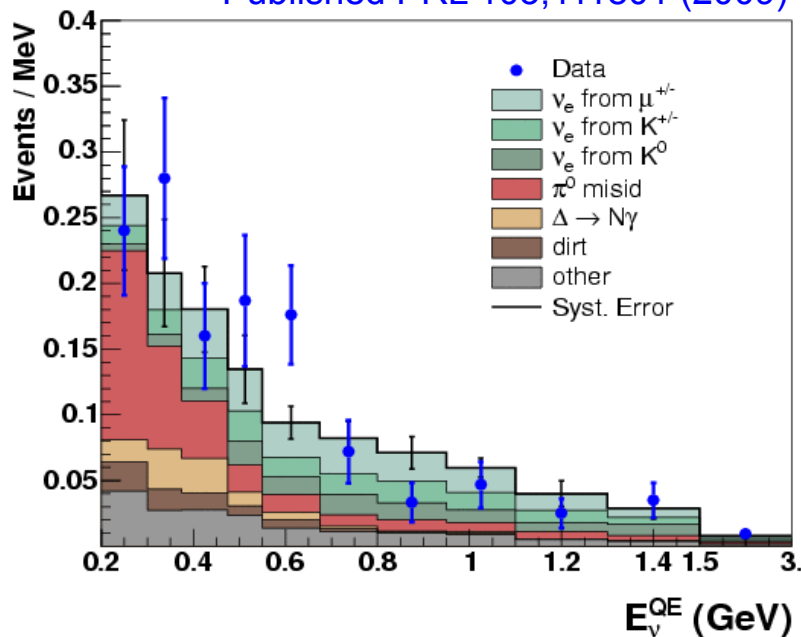
First Antineutrino mode MB results (2009)

- **3.4E20 POT** collected in anti-neutrino mode
- From 200–3000 MeV excess is 4.8 ± 17.6 (stat+sys) events.
- Statistically small excess (more of a wiggle) in 475–1250 MeV region
 - ➔ Only antineutrino's allowed to oscillate in fit
 - ➔ Limit from two neutrino fit excludes less area than sensitivity.
- No significant excess $E < 475$ MeV.
- Fits inconclusive with respect to LSND (need more stats)

Anti-Neutrino Exclusion Limits: 3.4E20 POT

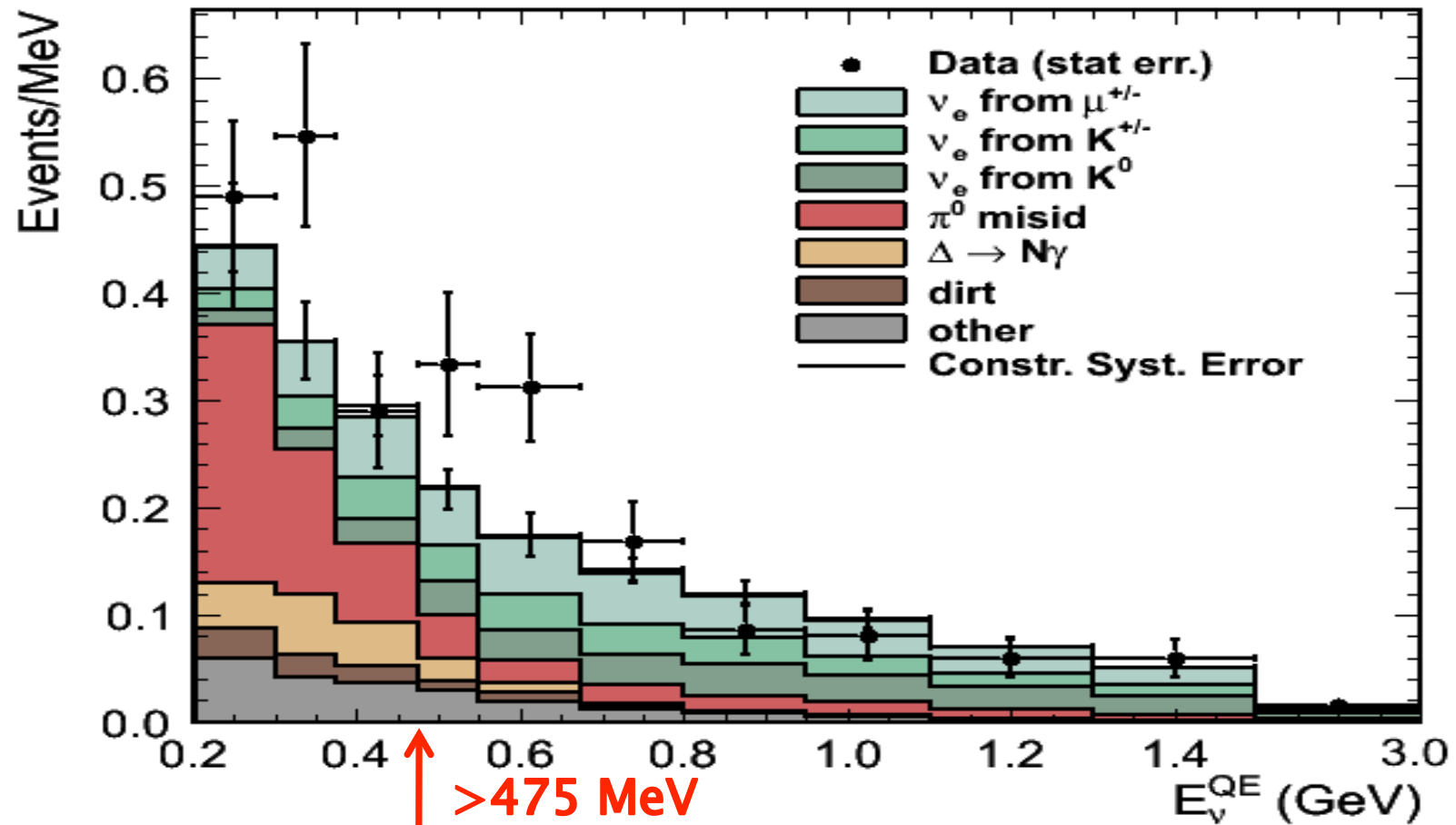


Published PRL 103,111801 (2009)



New Antineutrino Result with 5.66E20 POT (2010)

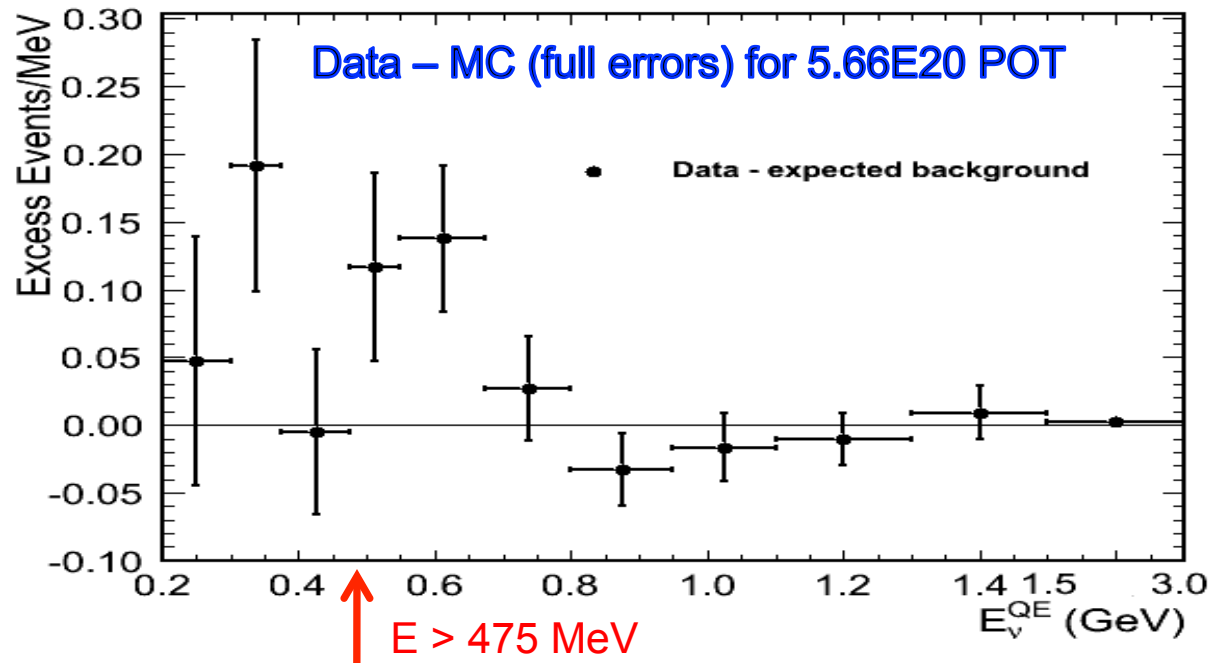
	200-475 MeV	475-1250 MeV	200-3000 MeV
Data	119	120	277
MC (stat+sys)	100.5 ± 14.3	99.1 ± 13.9	233.8 ± 22.5
Excess (stat)	18.5 ± 10.0 (1.9σ)	20.9 ± 10.0 (2.1σ)	43.2 ± 15.3 (2.8σ)
Excess (stat+sys)	18.5 ± 14.3 (1.3σ)	20.9 ± 13.9 (1.5σ)	43.2 ± 22.5 (1.9σ)



Testing the Antineutrino Null Hypothesis (5.66E20 POT)

- Model independent.
- At null look at the χ^2 distribution of fake experiments (thrown from null error matrix).

Fitting only $\bar{\nu}_e$ in the range 475 – 1250 MeV, null probability = 0.5%



Note: corresponding neutrino mode null probability is 40%

Data Checks for 5.66E20 POT

- ▶ Beam and Detector low level stability checks; beam stable to 2%, and detector energy response to 1%.
- ▶ $\bar{\nu}_\mu$ rates and energy stable over entire antineutrino run.
- ▶ Latest $\bar{\nu}_e$ data rate is 1.9σ higher than 3.4E20POT data set.
- ▶ Independent measurement of π^0 rate for antineutrino mode.
- ▶ Measured dirt rates are similar in neutrino and antineutrino mode.
- ▶ Measured wrong sign component stable over time and energy.
- ▶ Checked off axis rates from NuMI beam.
- ▶ Above 475 MeV, about two thirds of the electron (anti)neutrino intrinsic rate is constrained by simultaneous fit to $\bar{\nu}_\mu$ data.
 - New SciBooNE neutrino mode K^+ weight = $0.75 \pm 0.05(\text{stat}) \pm 0.30(\text{sys})$.
- ▶ One third of electron neutrino intrinsic rate come from K^0 , where we use external measurements and apply 30% error.
 - Would require $>3\sigma$ increase in K^0 normalization, but shape does not match well the excess.

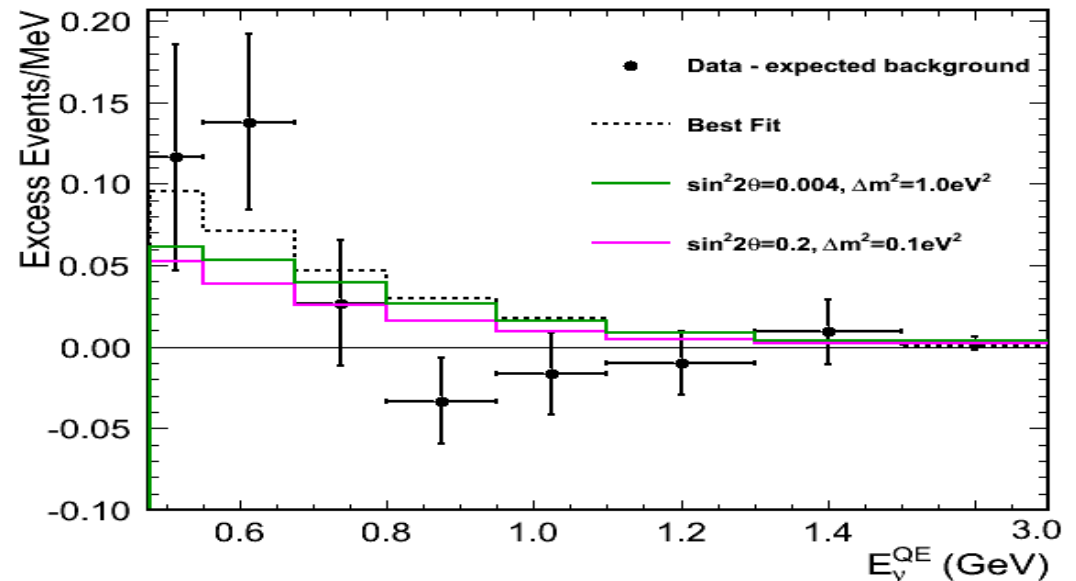
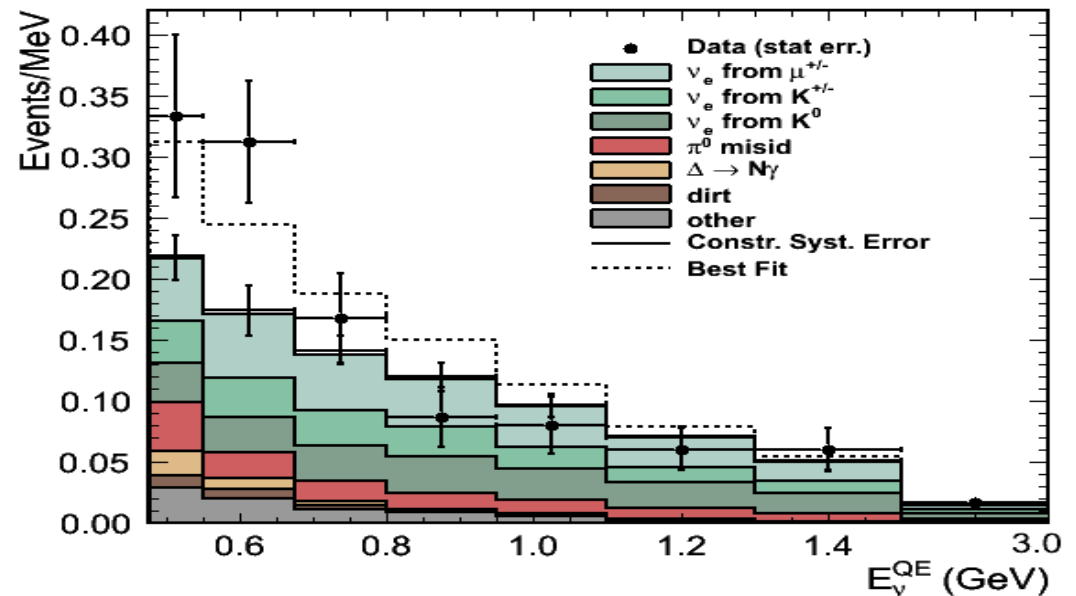
Comparison to LSND's best fit prediction and neutrino low energy expectation

	$E_\nu(\text{QE})$ [MeV]		
	200-475	475-1250	1250-3000
MC Background	100.5	99.1	34.2
Data	119	120	38
Excess	18.5 ± 14.3	20.9 ± 13.9	3.8 ± 5.8
LSND Best Fit	7.6	22.0	3.5
Expectation from ν low-E excess	11.6	0	0
LSND + Low-E	19.2	22.0	3.5

- Errors quoted here are stat+sys.
- Excess consistent with the expectation from LSND and adding the low energy excess scaled for neutrinos (wrong-sign).
- Expected 67 events at low energy (200–475 MeV) if neutrino low E excess is due to a Standard Model NC gamma-ray mechanism, e.g. Axial Anomaly.

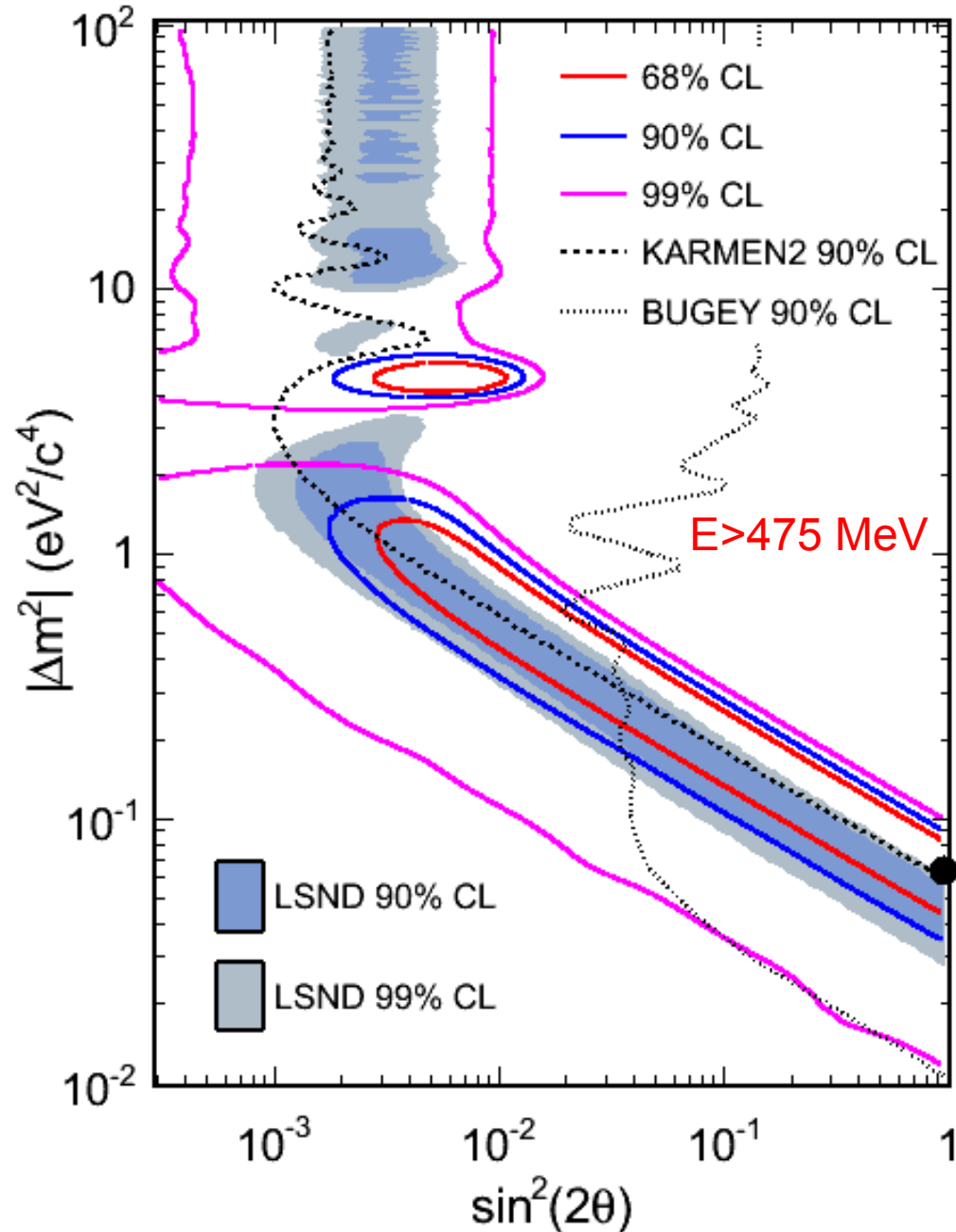
Updated Antineutrino mode MB results for $E > 475$ MeV: (official oscillation region)

- Results for **5.66E20 POT**.
- Maximum likelihood fit.
- Only antineutrinos allowed to oscillate.
- $E > 475$ MeV region is free of effects of low energy neutrino excess. This is the same official oscillation region as in neutrino mode.
- Published PRL 105, 181801 (2010)



Updated Antineutrino mode MB results for $E > 475$ MeV (official oscillation region)

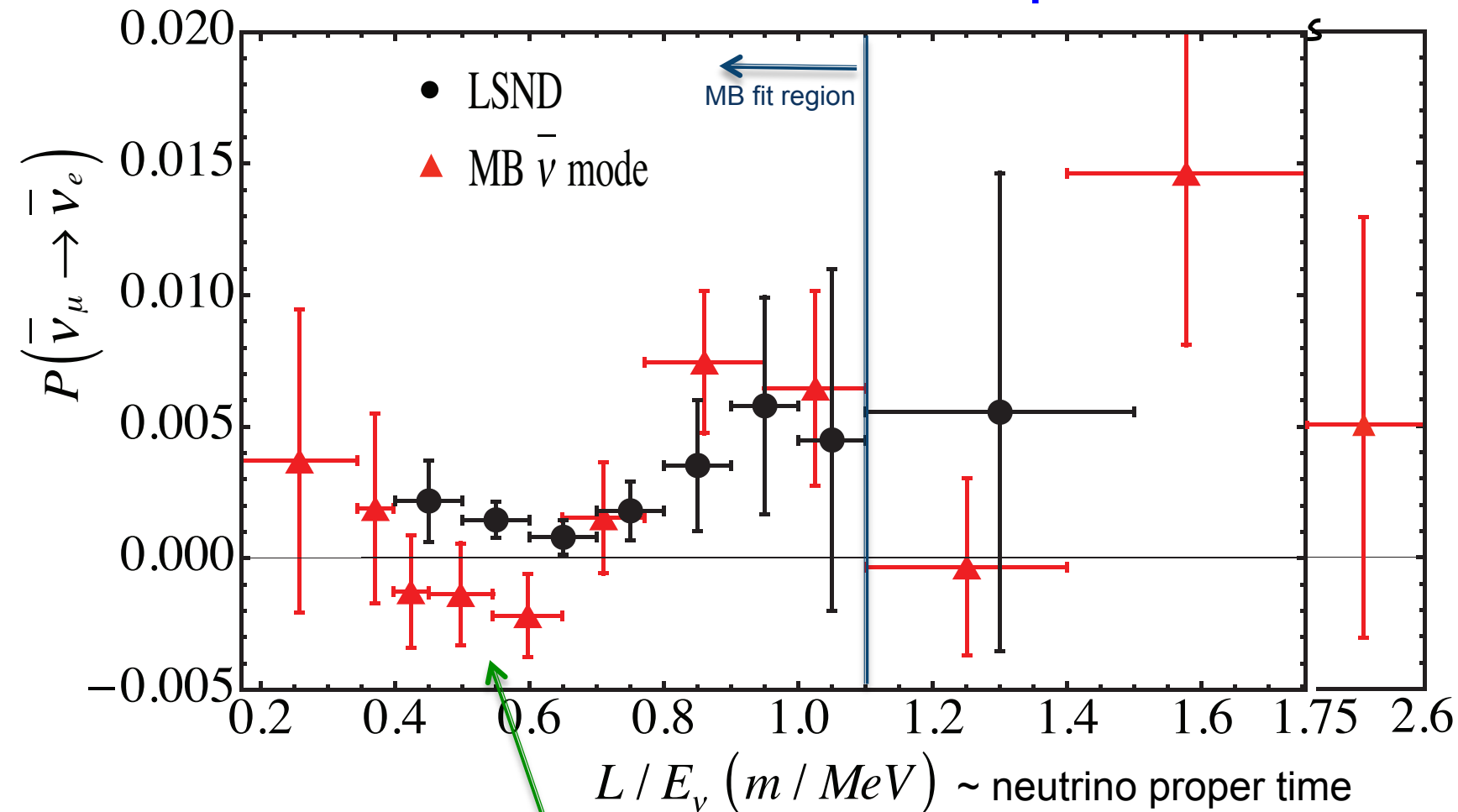
- Results for **5.66E20 POT**
- Maximum likelihood fit.
- Null excluded at 99.4% (2.7σ) with respect to the two neutrino oscillation fit.
- Best Fit Point $P(\chi^2) = 8.7\%$
($\Delta m^2, \sin^2 2\theta$) = (0.064 eV², 0.96)
- Published PRL 105, 181801 (2010)
- Fits similar for $E > 200$ MeV with and without inclusion of low energy neutrino excess.



LSND and MiniBooNE Oscillation Probability

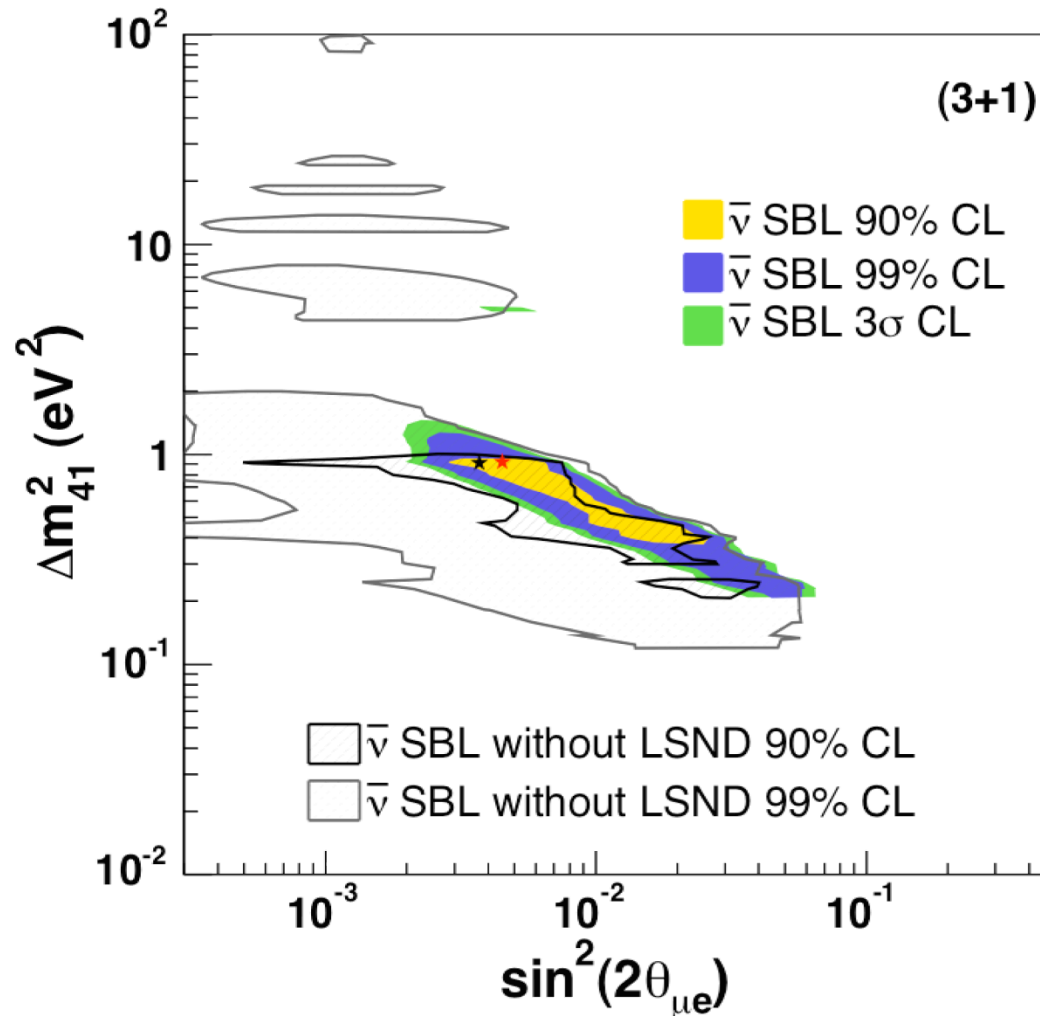
Direct Data Comparison

PRL 105, 181801 (2010)



KARMEN ($\bar{\nu}_\mu \rightarrow \bar{\nu}_e$) reported no signal around $L/E \sim 0.5$

Combined Short Baseline Antineutrino Appearance Fits (5.66E20 POT MB, LSND, KARMEN, Bugey, CHOOZ)



Updated from G. Karagiorgi et al., PRD80, 073001 (2009)

Best 3+1 Fit:

$$\Delta m_{41}^2 = 0.92 \text{ eV}^2$$

$$\sin^2 2\theta_{\mu e} = 0.0045$$

Prob. = 90%

Predicts $\bar{\nu}_\mu$ & $\bar{\nu}_e$ disappearance of

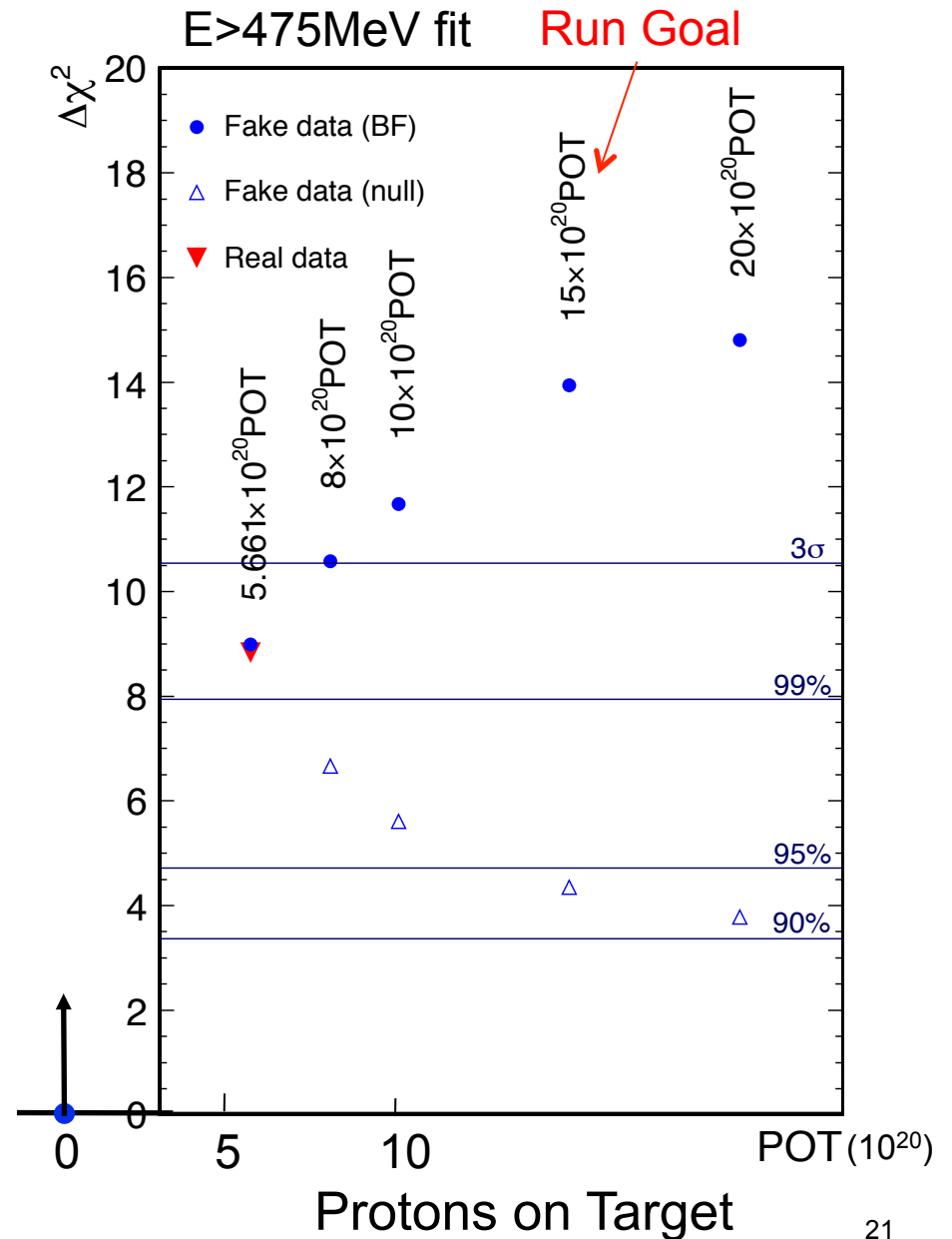
$$\sin^2 2\theta_{\mu\mu} \sim 37\%$$

$$\sin^2 2\theta_{ee} \sim 4.3\%$$

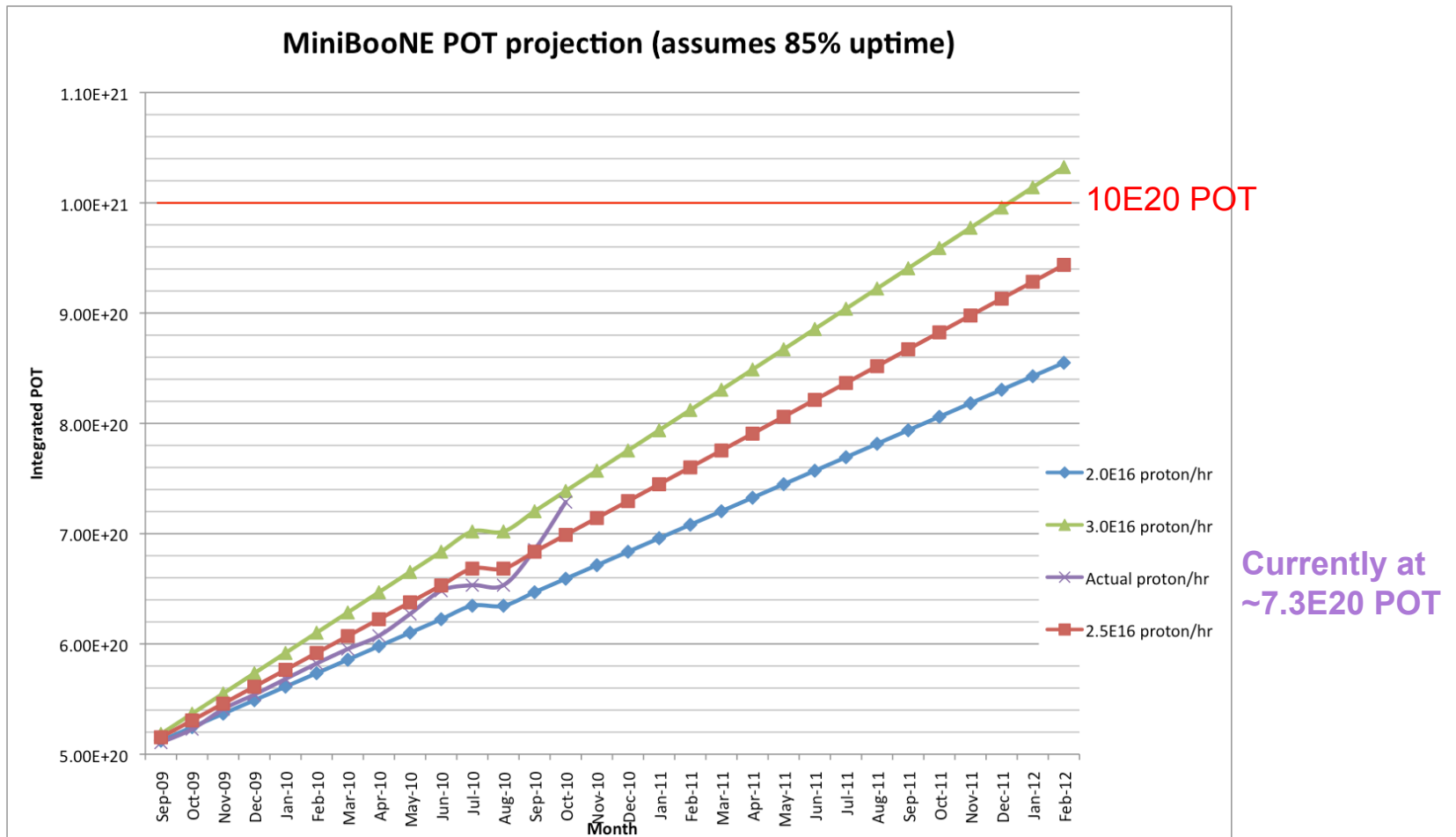
Motivation and Logistics of Further Running

Future sensitivity in $\bar{\nu}$ Data

- Potential 3σ exclusion of null point assuming best fit signal
- If no signal, then drop below 95%.
- Addition of statistics plateaus around $15E20$ POT.

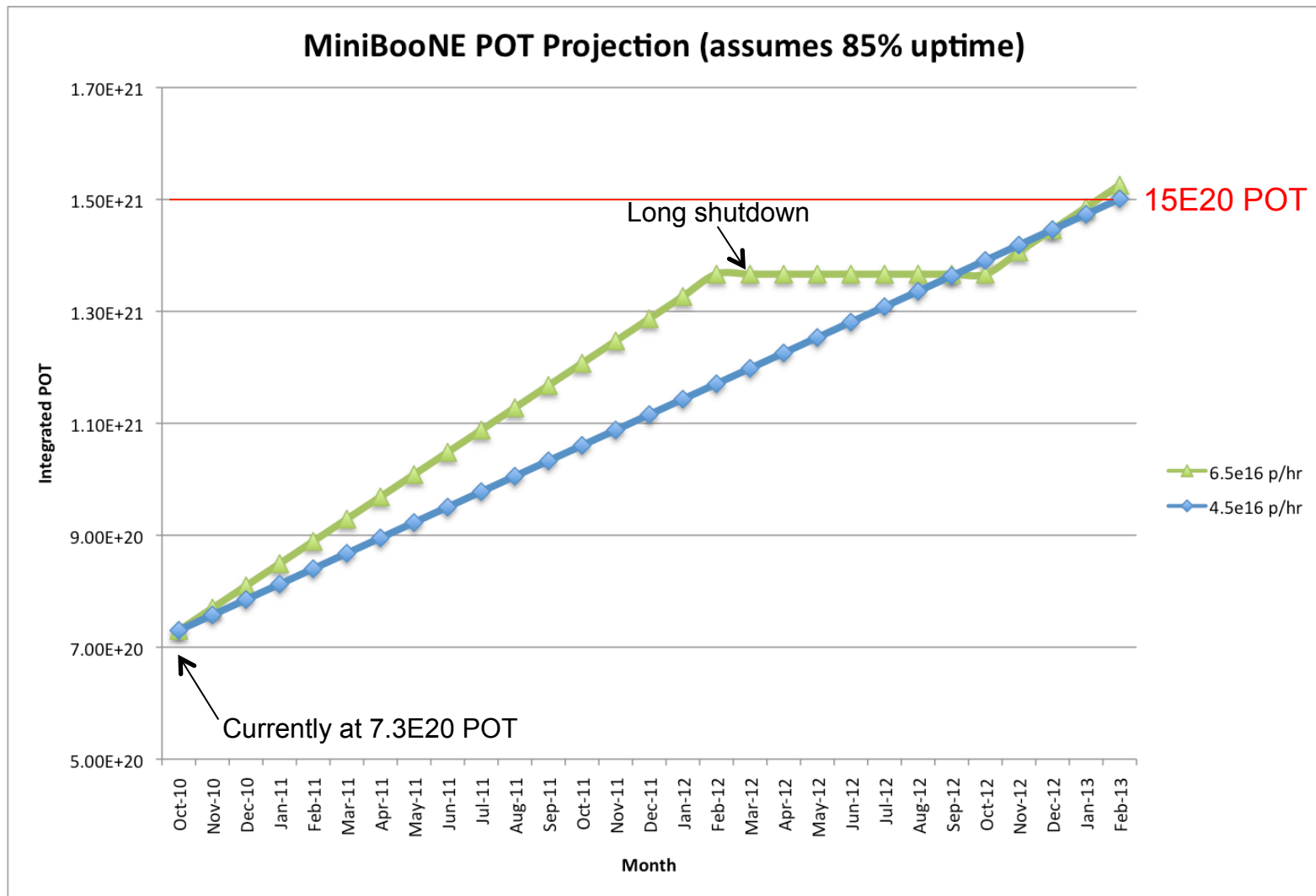


POT Projection thru 2012 Shutdown



Historically running at $\sim 2.5\text{E}16$ p/hr, will reach $\sim 10\text{E}20$ POT by 2012 shutdown

Required POT rate to collect 15E20 POT by start of uBooNE neutrino run (January 2013) with and without long shutdown in 2012



Require rate increased to 4.5e16 p/hr (no shutdown) or 6.5e16 p/hr (shutdown) to reach POT goal. 23

Realistic POT Projection to start of uBooNE neutrino run (January 2013)

POT Collection Period	N Weeks	Rate [10^{19} POT/wk]	POT $\times 10^{20}$
Published through 3/14/10			5.7
Nominal running 3/15/10-9/19/10	27	0.4	1.1
NuMI down 9/19/10-11/7/10	7	1.0	0.7
Nominal running 11/8/10-3/1/12	59	0.4	2.4
+10% Shielding Assess. 1/1/11-3/1/12	52	0.04	0.2
Total Through March 2012			10.1
Running 3/1/12-1/1/13 (Run IIe/No Run IIe)	39/5	0.44	1.7/0.2
Total Through Jan 2013			11.8/10.3
Other possibilities:			
3 Month dedicated run (no NuMI)	12	1.0	1.2
Adding 1 Hz-year to Booster	44		1.1

With extended Tevatron run, a 3 month NuMI off run, and adding 1Hz to the Booster, can reach $\sim 14E20$ POT by 2013.

Other benefits of running till 2013:

- keep beamline running and tuned up
- monitor beam during uBooNE start up

Logistics of Extra Running

- ▶ 42 collaborators from 13 institutions on board for extended running (3 new students and 1 new PD)
 - Critical mass of experts to perform oscillation analysis
 - Remote shifts reduce shift burden
 - Hired full time shifter to take $\frac{3}{4}$ of all graveyard shifts.
- ▶ Current (2nd) horn and target has run 6 years and $\frac{1}{4}$ billion pulses
 - ~1 gallon/day water leak and intermittent ground faults.
 - Dehumidifier installed after first horn failure is extracting lost water and allows continued running.
 - Have a 3rd spare horn/target ready to go if horn #2 fails.
- ▶ Enough detector parts to continue running
 - New HVAC installed in 2009 has improved stability
 - May need to purchase new laser head (\$20k)
 - Upgrade DAQ and computing infrastructure (\$50k)

MiniBooNE Analysis in the Works

- $\bar{\nu}_e$ with added statistics
- $\nu_e/\bar{\nu}_e$ ratio, i.e. quantify the difference between neutrino and antineutrino oscillations
- ν_μ & $\bar{\nu}_\mu$ disappearance (joint with SciBooNE)
- Include Kaon constraint from SciBooNE
- NuMI data oscillation analysis
- Re-optimize oscillation analysis cuts, and BDT
- RWM fine timing (check of backgrounds and exotic signals)
- Sidereal time analysis (Lorentz Violation)
- HARP thick target
- Wrong sign analysis (neutrino content of antineutrino beam)
- Various antineutrino cross sections (CCQE, NC, etc)

Have published 17 papers on oscillations and cross sections
MiniBooNE analysis is still active, more papers on the way

Summary:

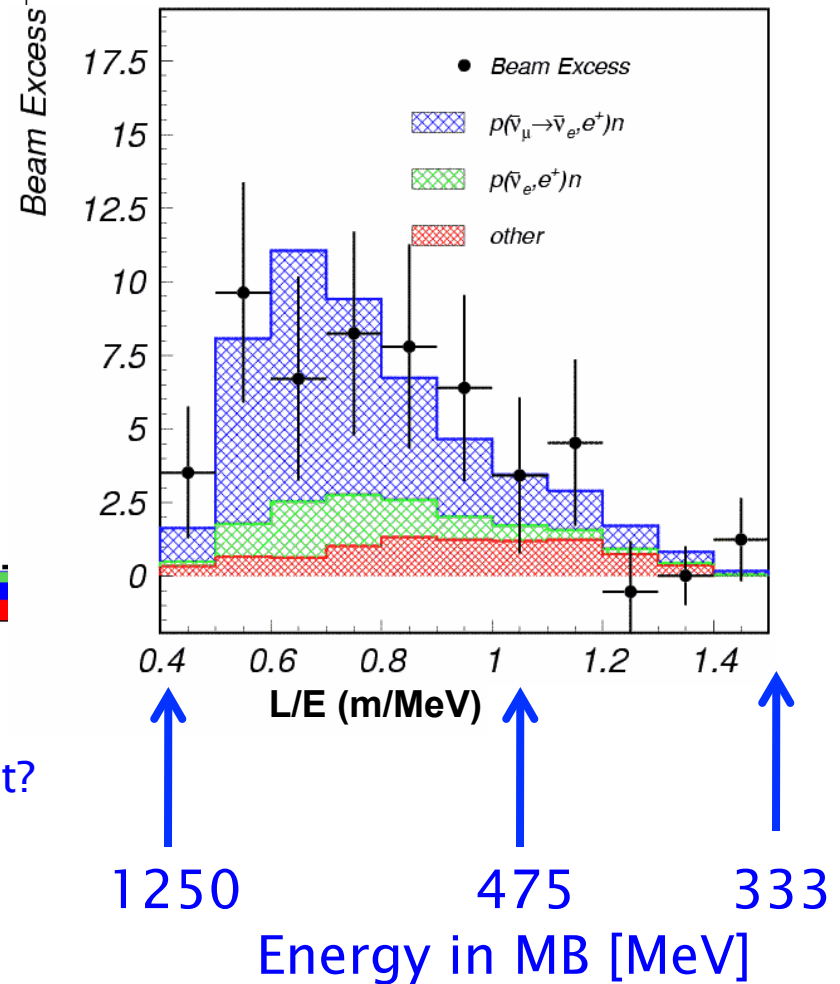
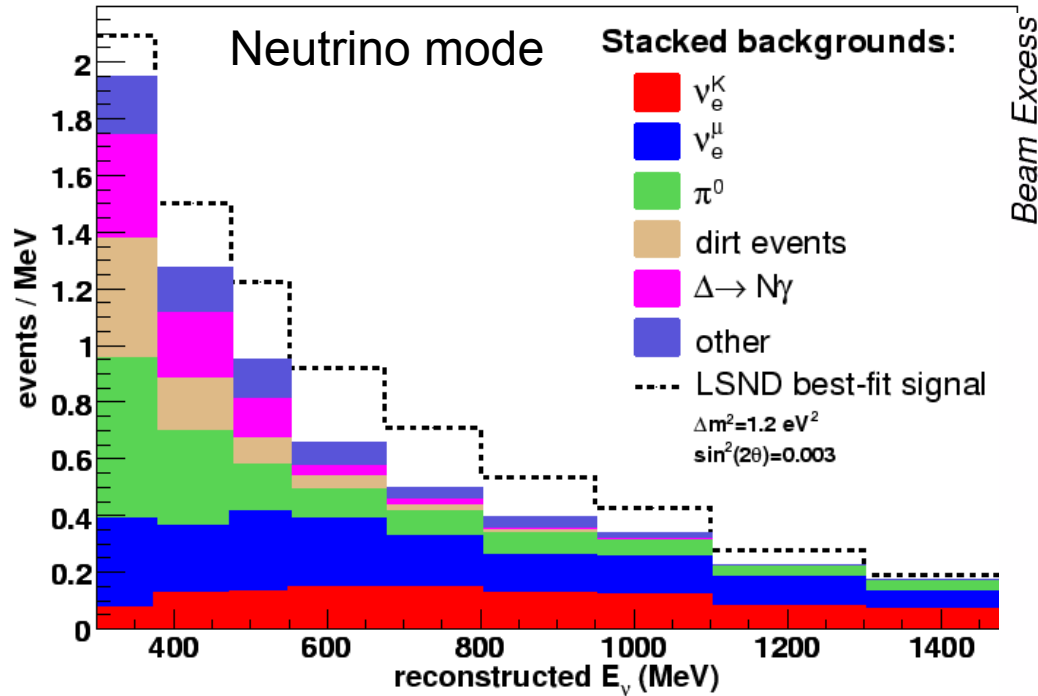
- ▶ The MiniBooNE ν_e and $\bar{\nu}_e$ appearance picture starting to emerge is the following:
 - 1) **Neutrino Mode:**
 - a) $E < 475$ MeV: An unexplained 3σ electron-like excess.
 - b) $E > 475$ MeV: A two neutrino fit inconsistent with LSND at the 98% CL.
 - 2) **Anti-neutrino Mode:**
 - a) $E < 475$ MeV: A small 1.3σ electron-like excess.
 - b) $E > 475$ MeV: An excess that is 0.5% consistent with null. Two neutrino oscillation fits consistent with LSND at 99.4% CL relative to null.
- ▶ Apparent difference between neutrino and antineutrino results.
- ▶ Neutrino result limited by systematic error (need near detector)
- ▶ Antineutrino result limited by statistics (need 1.5×10^{20} POT)
- ▶ If these results are confirmed, then we are dealing with two experiments that observe apparent oscillations at the ~ 1 eV² mass scale.

The Request

- ▶ MiniBooNE requests additional antineutrino running to collect a total of 15.0×10^{20} POT in antineutrino mode. This will allow a powerful statistical check of the current MiniBooNE antineutrino oscillation result that is consistent with LSND. The experiment further requests that these POT be delivered by early 2013 if possible.

Backup Slides

Reminders of some pre-unblinding choices

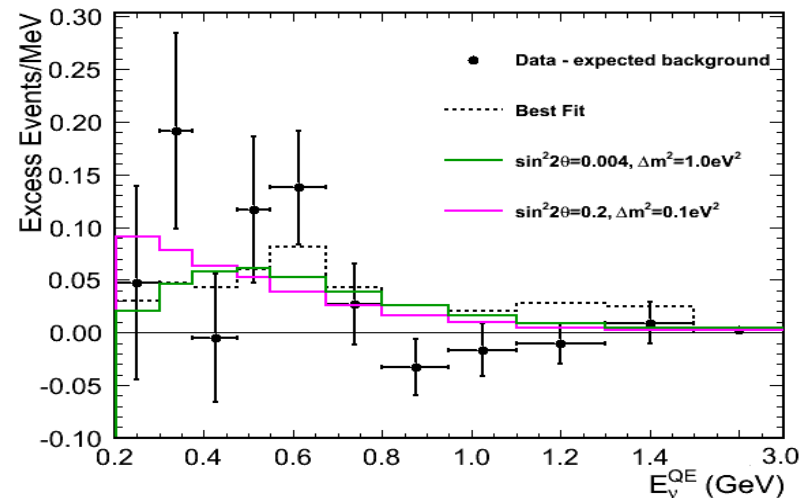
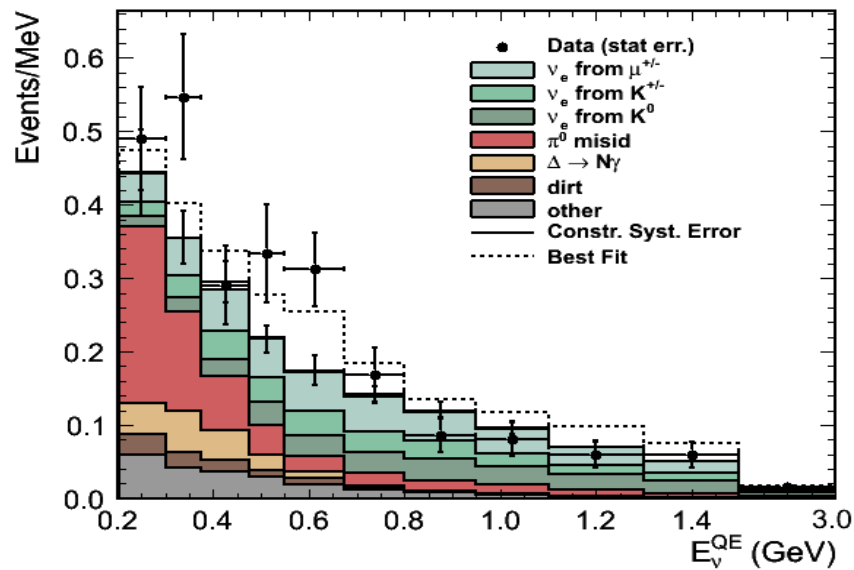
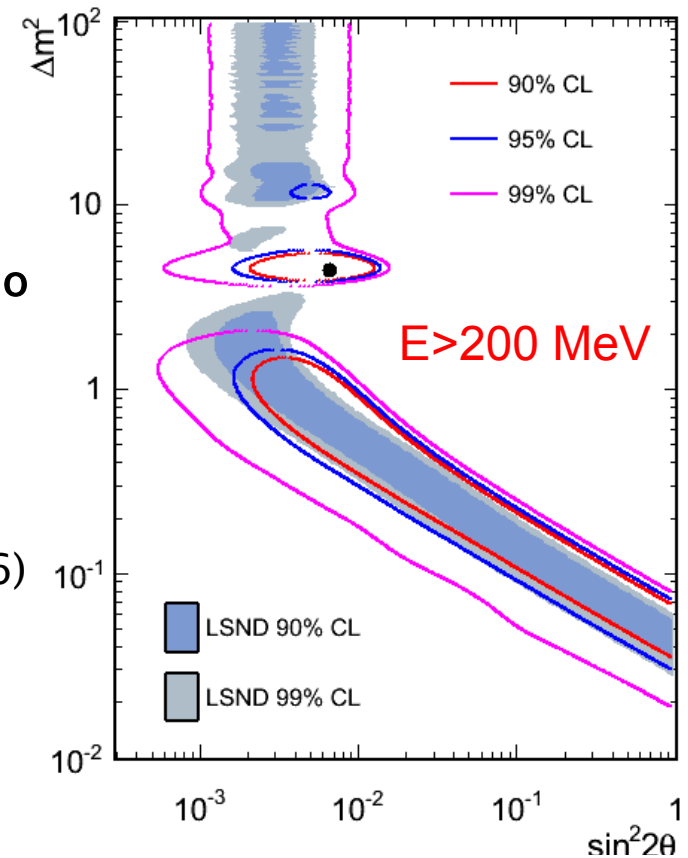


Why is the 200-475 MeV region unimportant?

- Large backgrounds from mis-ids reduce S/B.
- Many systematics grow at lower energies, especially on signal.
- Most importantly, not a region of L/E where LSND observed a significant signal!

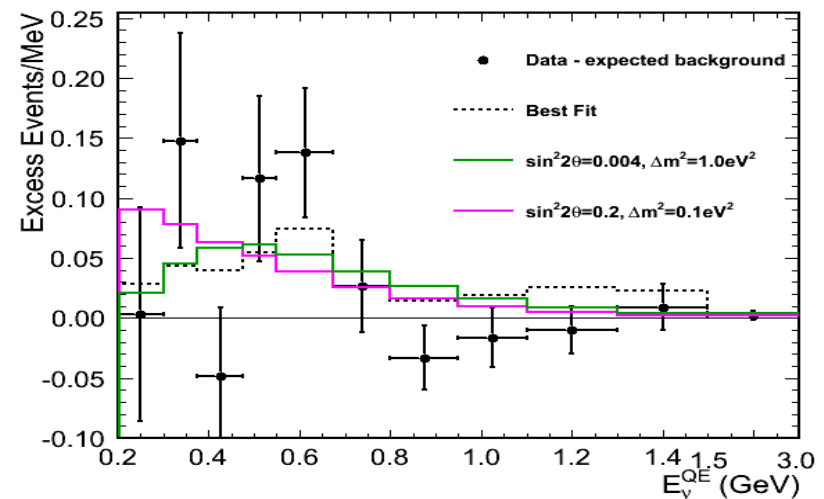
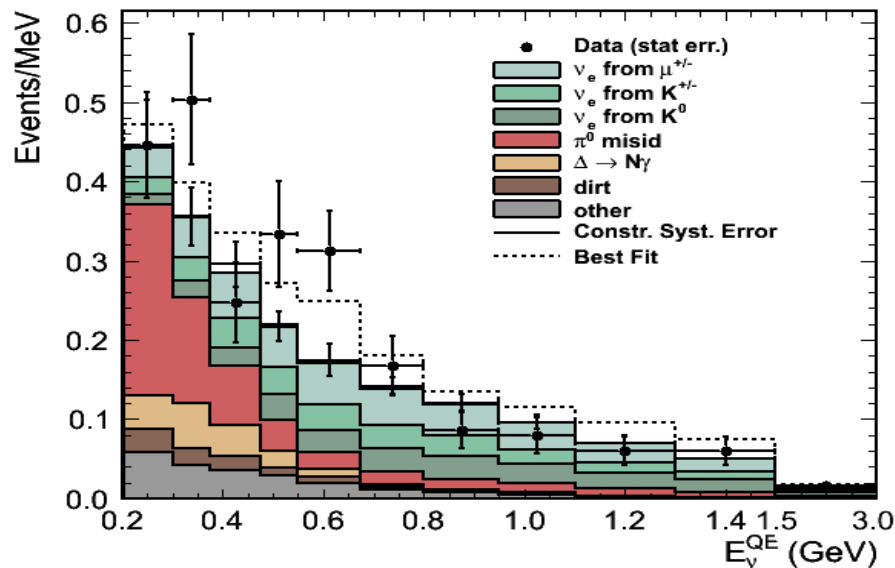
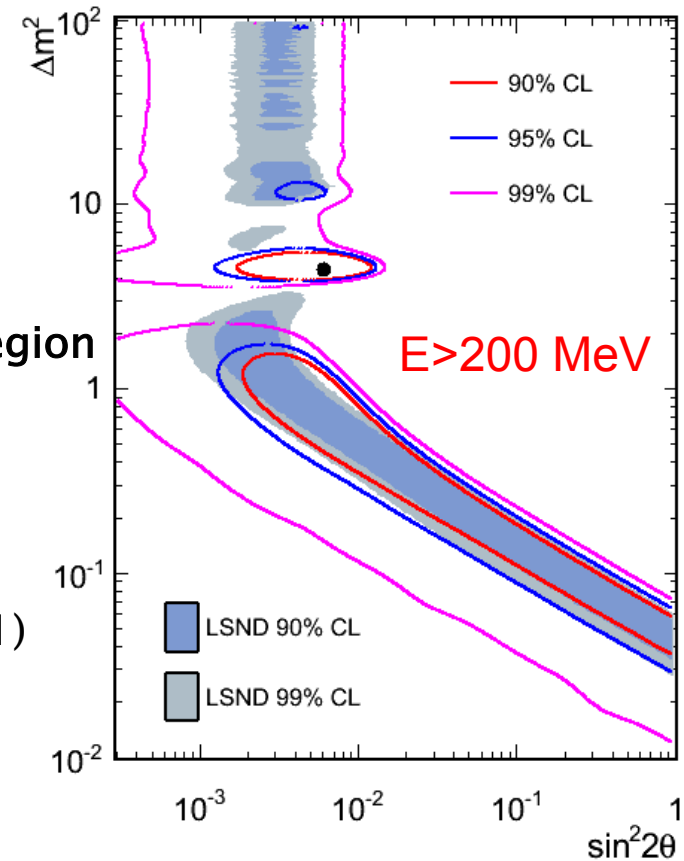
New Antineutrino mode MB results for $E > 200$ MeV:

- Results for **5.66e20 POT**.
- Does not include effects (subtraction) of neutrino low energy excess.
- Maximum likelihood fit method.
- Null excluded at 99.6% with respect to the two neutrino oscillation fit (model dependent).
- Best Fit Point $(\Delta m^2, \sin^2 2\theta) = (4.42 \text{ eV}^2, 0.0066)$
 $P(\chi^2) = 10.9\%$.

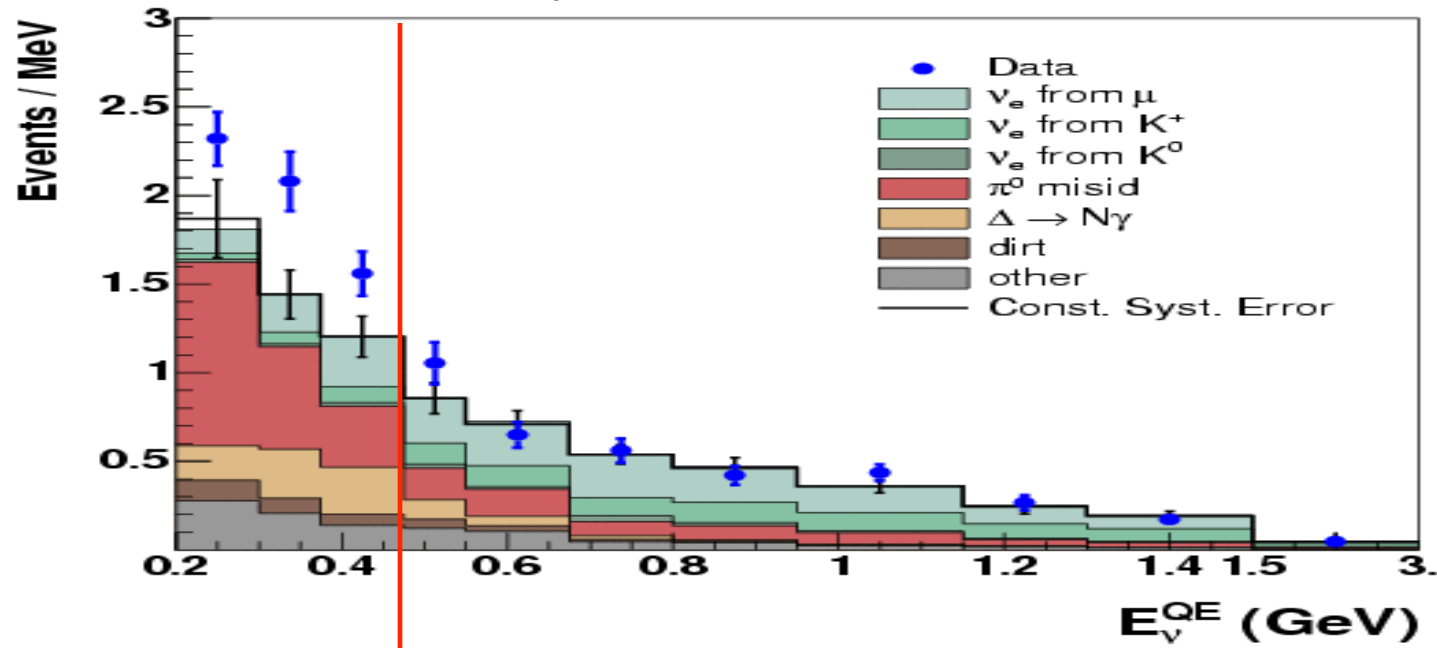


New Antineutrino mode MB results for $E > 200$ MeV: Include low E Effects

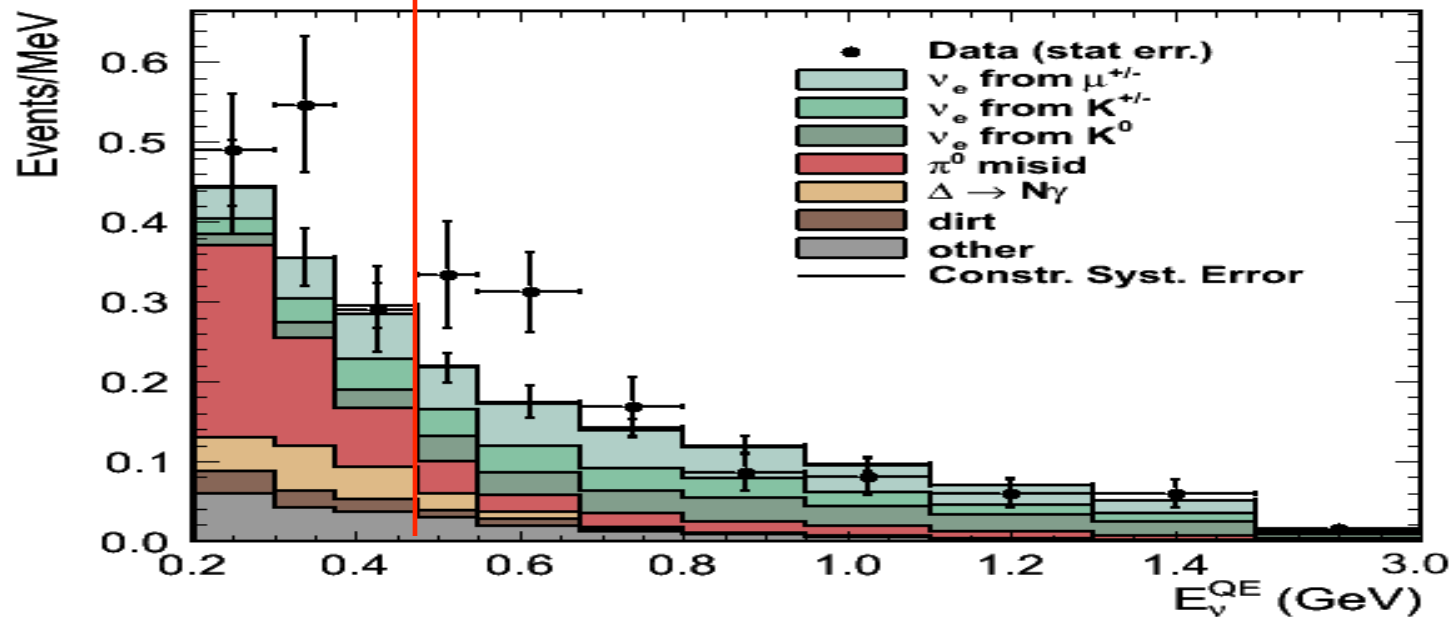
- Results for **5.66e20 POT**.
- Assume simple scaling of neutrino low energy excess; subtract 11.6 events from low energy region (200–475 MeV).
- Maximum likelihood fit method.
- Null excluded at 99.6% with respect to the two neutrino oscillation fit (model dependent).
- Best Fit Point $(\Delta m^2, \sin^2 2\theta) = (4.42 \text{ eV}^2, 0.0061)$
 $P(\chi^2) = 7.5\%$.



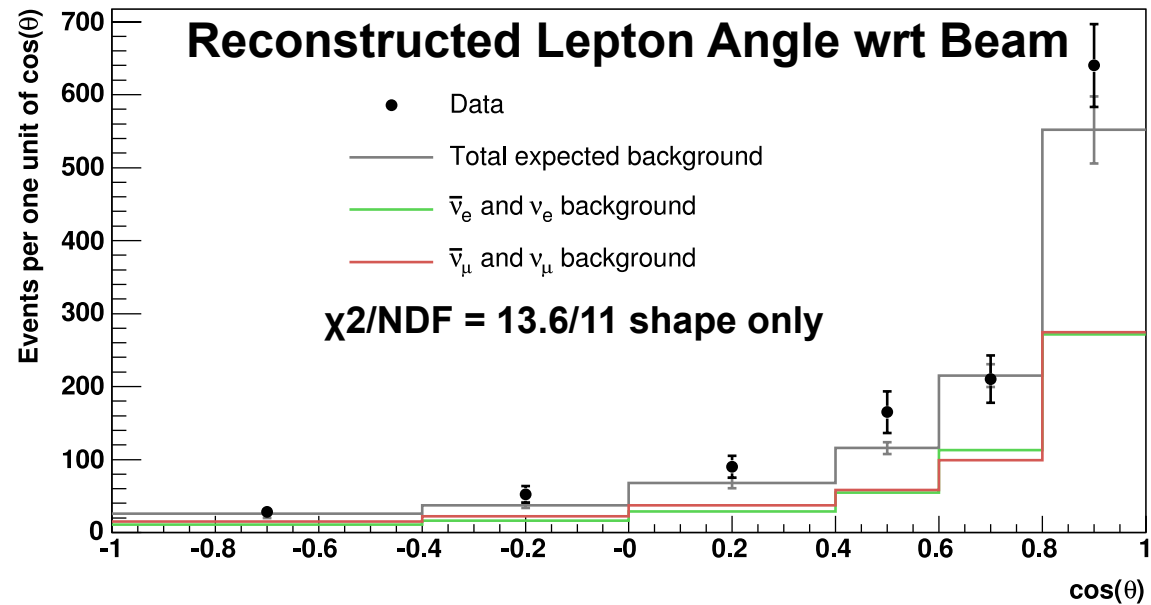
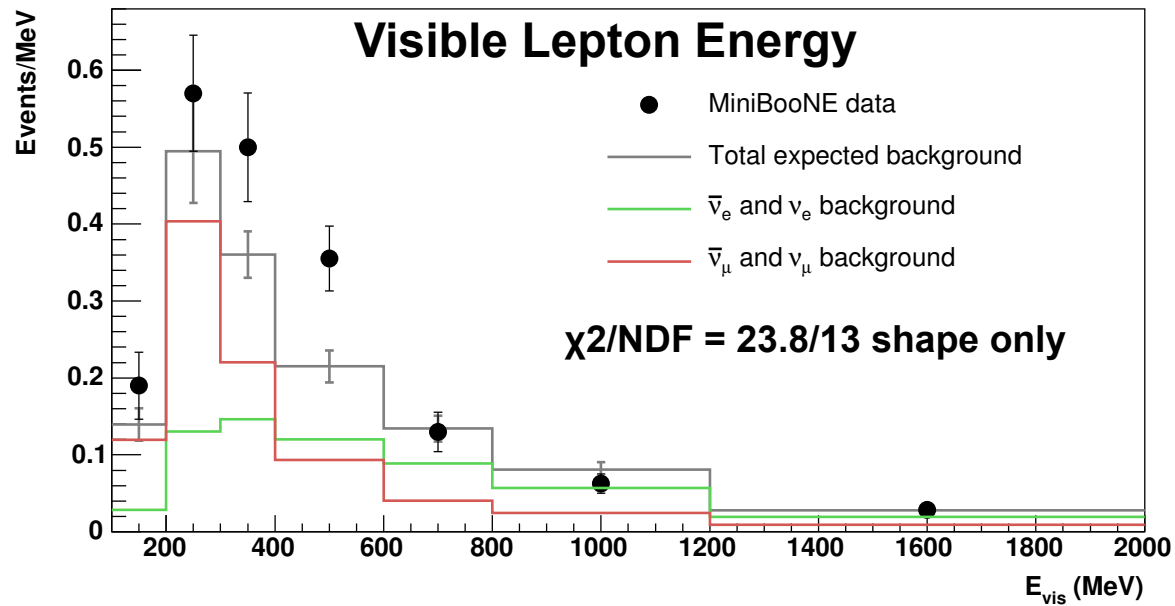
Neutrino ν_e Appearance Results (6.5E20POT)



Antineutrino $\bar{\nu}_e$ Appearance Results (5.66E20POT)



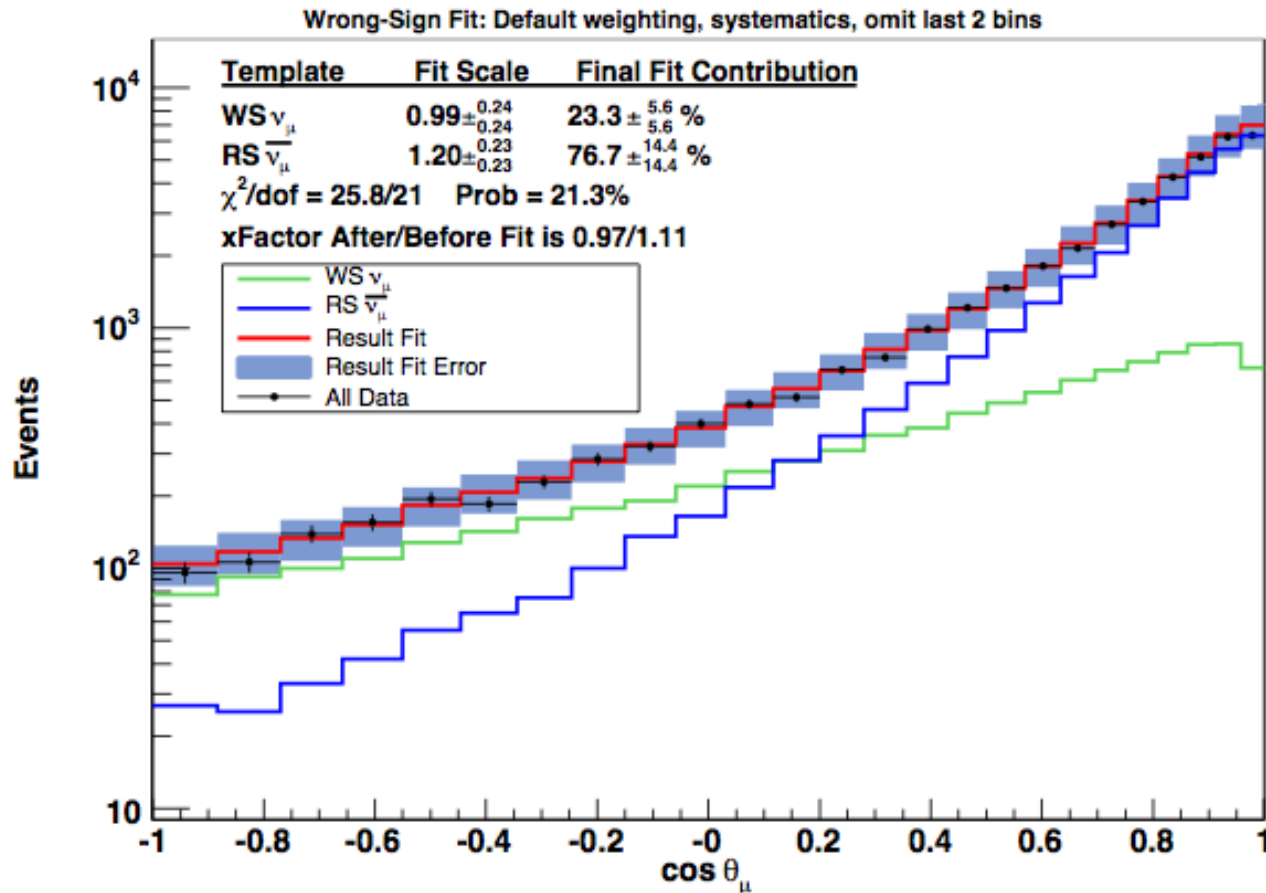
Other $\bar{\nu}_e$ kinematic distributions for 5.66E20 POT



Background systematic uncertainties:
Many errors are similar between neutrino and antineutrino mode

Source	$\bar{\nu}$ mode uncer. (%)		ν mode uncer. (%)	
	200-475	475-1100	200-475	475-1100
E_{ν}^{QE} range (MeV)				
Flux from π^+/μ^+ decay	0.4	0.9	1.8	2.2
Flux from π^-/μ^- decay	3.0	2.3	0.1	0.2
Flux from K^+ decay	2.2	4.7	1.4	5.7
Flux from K^- decay	0.5	1.2	-	-
Flux from K^0 decay	1.7	5.4	0.5	1.5
Target and beam models	1.7	3.0	1.3	2.5
ν cross section	6.5	13.0	5.9	11.9
NC π^0 yield	1.5	1.3	1.4	1.9
Hadronic interactions	0.4	0.2	0.8	0.3
External interactions (dirt)	1.6	0.7	0.8	0.4
Optical model	8.0	3.7	8.9	2.3
Electronics & DAQ model	7.0	2.0	5.0	1.7
Total (unconstrained)	13.5	16.0	12.3	14.2

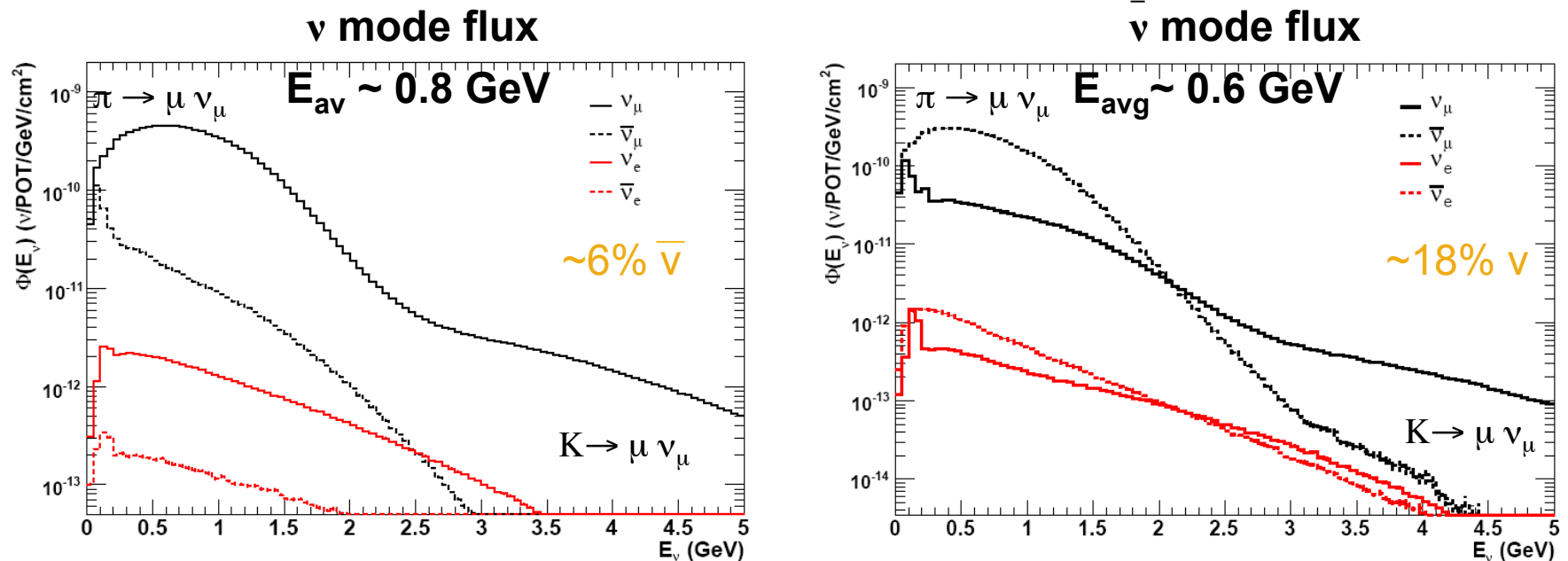
Wrong-sign Contribution Fits



- Wrong-sign fit from angular distribution constrains WS
- Central value from fit used in background prediction
- Errors on WS flux and xsec propagated through osc analyses

MiniBooNE Flux (Flux paper arXiv: 0806.1449)

Appearance experiment: it looks for an excess of electron neutrino events in a predominantly muon neutrino beam



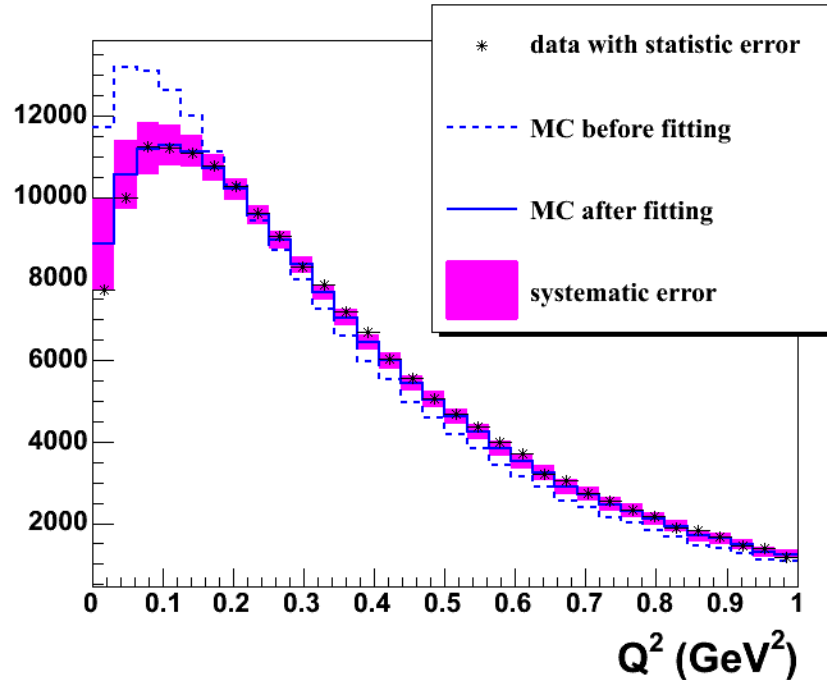
Subsequent decay of the μ^+ (μ^-) produces $\bar{\nu}_e$ (ν_e) intrinsics $\sim 0.5\%$

neutrino mode: $\nu_\mu \rightarrow \nu_e$ oscillation search

antineutrino mode: $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillation search

CCQE Scattering (*Phys. Rev. Lett* 100, 032301 (2008))

186000 muon neutrino events



From Q^2 fits to MB ν_μ CCQE data:

M_A^{eff} -- effective axial mass

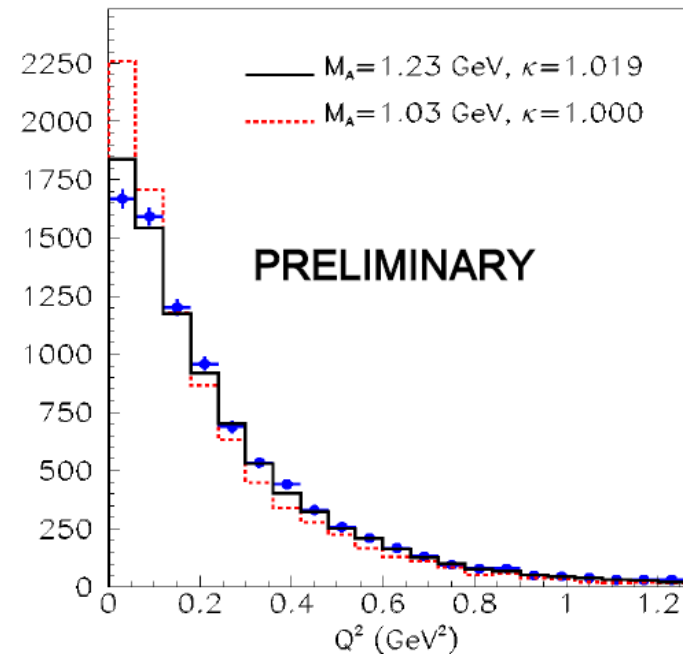
κ -- Pauli Blocking parameter

From electron scattering data:

E_b -- binding energy

p_f -- Fermi momentum

14000 anti-muon neutrinos



Fermi Gas Model describes CCQE

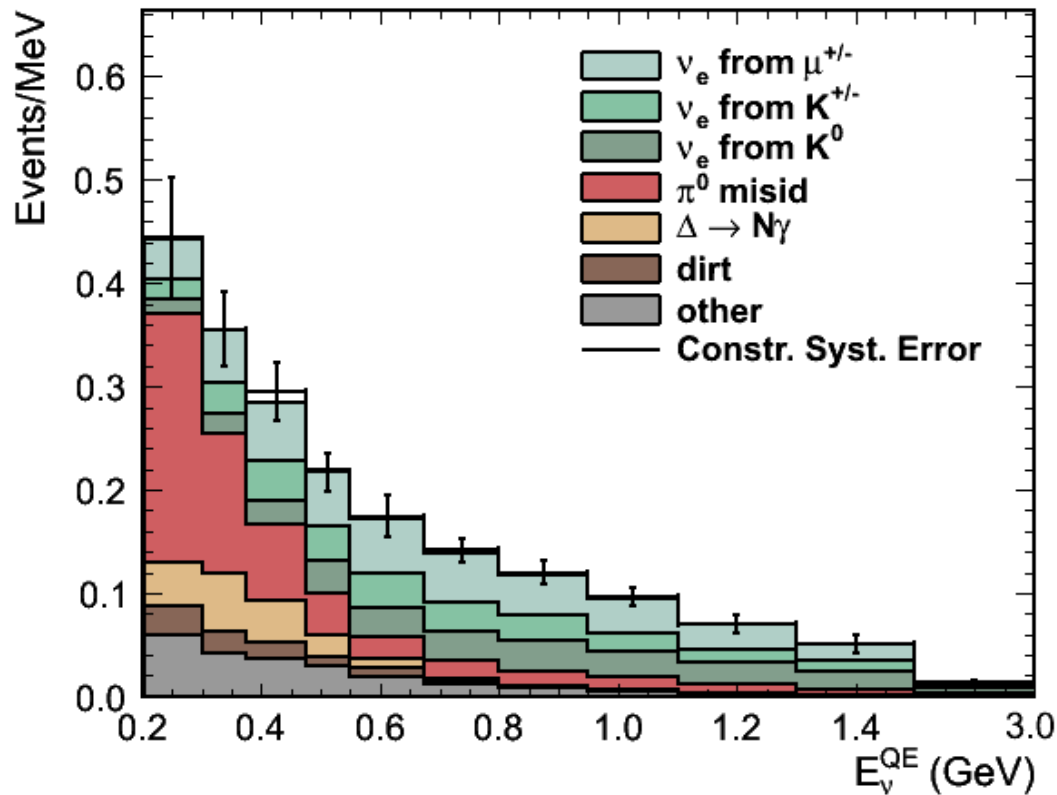
ν_μ data well

$$M_A = 1.23 \pm 0.20 \text{ GeV}$$

$$\kappa = 1.019 \pm 0.011$$

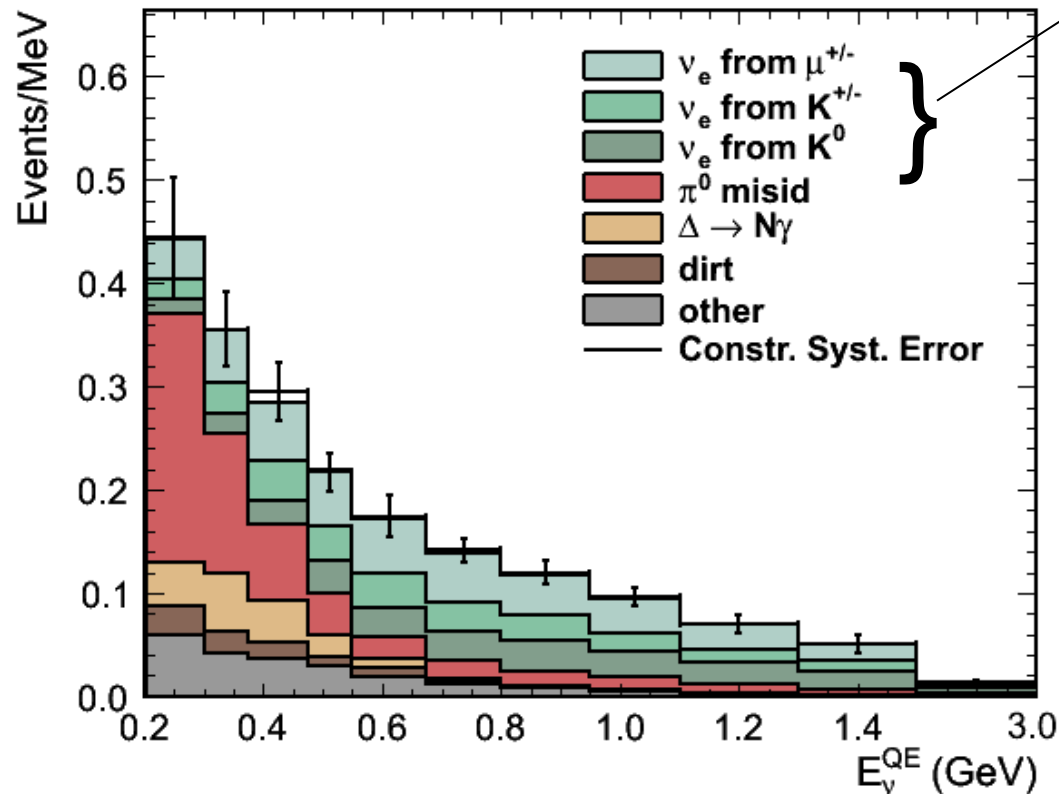
Also used to model ν_e and $\bar{\nu}_e$ interactions

Background prediction $\bar{\nu}$ mode

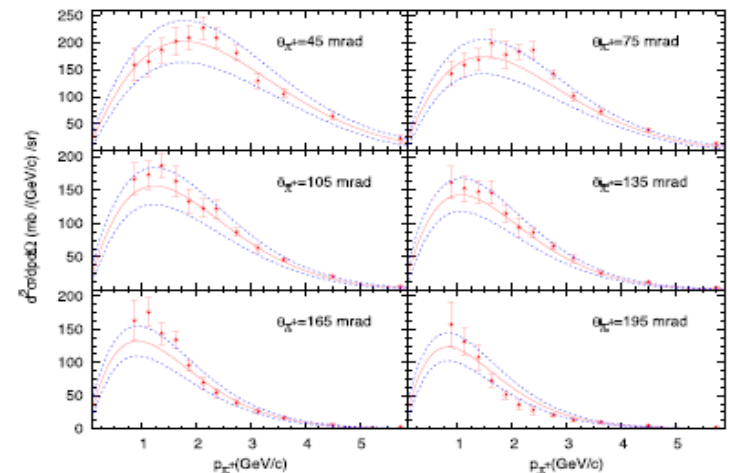


5.66e20 Protons on Target			
	200-475	475-125	
μ^\pm	13.45	31.39	Intrinsic ν_e
K^\pm	8.15	18.61	
K^0	5.13	21.2	
Other ν_e	1.26	2.05	
NC π^0	41.58	12.57	Mis-ID
$\Delta \rightarrow N\gamma$	12.39	3.37	
dirt	6.16	2.63	
ν_μ	4.3	2.04	
Other ν_μ	7.03	4.22	
Total	99.45	98.08	

High Energy Backgrounds



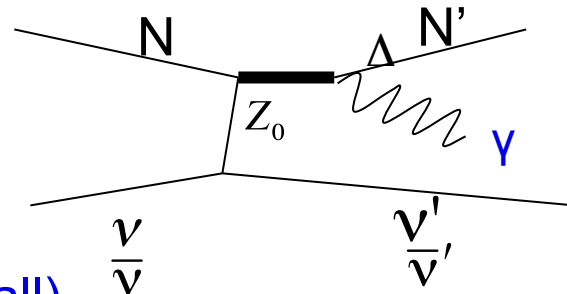
- Intrinsic $\bar{\nu}_e$ & ν_e
 - External measurements
 - HARP p+Be for π^\pm



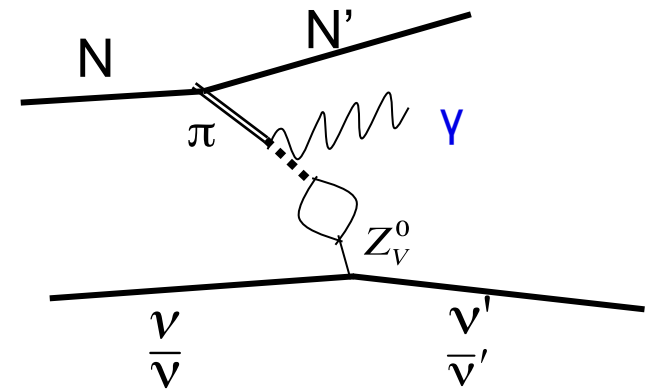
- – Sanford-Wang fits to world K^+ / K^0 data
- $\bar{\nu}_u$ & ν_u constraint
- SciBooNE neutrino mode K^+ weight = $0.75 \pm 0.05(\text{stat}) \pm 0.30(\text{sys})$.

Backgrounds: $\text{Order}(\alpha_{\text{QED}} \times \text{NC})$, single photon FS

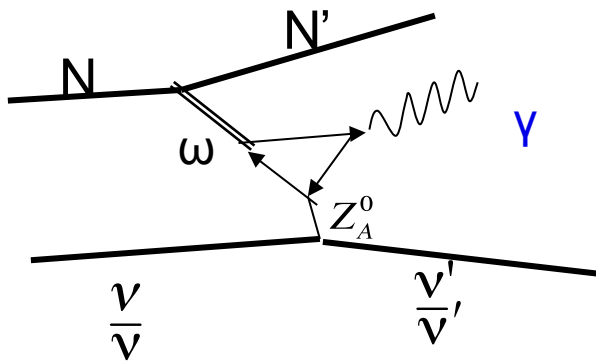
Radiative Delta Decay
(constrained by $\text{NC}\pi^0$)
($G^2\alpha/\alpha_s$)



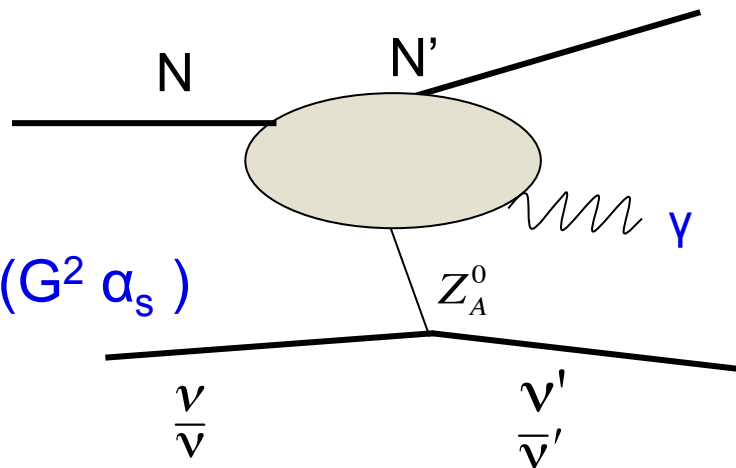
Other PCAC (small)



Axial Anomaly (small)



All order ($G^2 \alpha_s$)



*$\nu - \bar{\nu}$ comparison to test
neutral current hypothesis*